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Proyecto Fin de Carrera

Estudio de lechos fluidizados de esferas aplicados a reactores nucleares HTR
(1/2)

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"En la vida, no hay nada que temer,

sólo hay que comprender"

(Marie Curie)

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Índice general

I MEMORIA **15**

1. INTRODUCCIÓN **17**

1.1. Motivación 17

1.2. Objetivos 18

1.3. Organización de la memoria 19

2. TAREAS DESARROLLADAS **20**

3. FUNDAMENTOS TEÓRICOS **21**

3.1. Teoría de lechos fluidizados 21

3.2. Modelos teóricos 22

3.2.1. Método de Elementos Discretos (D.E.M.) 23

3.2.2. Aproximación por dinámica de medios continuos 23

3.3. Estado del arte: experimentos realizados 24

3.3.1. AVR 24

3.3.2. THTR-300 24

3.3.3. ANABEK 25

3.3.4. Teoría de Silos 25

3.4. Desarrollo de un modelo fluido 26

3.4.1. Descripción del sistema granular 26

3.4.2. Validez de la aproximación al continuo 27

3.4.3. Acoplamiento de variables 28

3.4.4. Definición de las condiciones de contorno 29

3.4.5. Propiedades de los materiales 30

3.4.6. Geometría y condiciones de operación 30

4. RESULTADOS **31**

4.1. Introducción 31

4.2. Validez de las hipótesis 31

4.2.1. Validez de las simplificaciones 31

4.2.2. Validez de las condiciones de contorno 32

4.3. Resultados y validación de las simulaciones 33

4.3.1. Líneas de corriente y características del flujo 33

4.3.2. Distribución de tiempos de residencia 33

4.3.3. Perfiles de velocidad 34

5. CONCLUSIONES Y TRABAJO FUTURO **35**

5.1. Conclusiones 35

5.2. Trabajo futuro 36

II “ANEXO I: ANALYSIS OF PEBBLE BEDS IN HIGH TEMPERATURE REACTORS” **37**

A. INTRODUCTION **39**

B. MOTIVATION AND OBJECTIVES **41**

B.1. Pebble Beds in the operation of nuclear reactors 41

B.2. Objectives in the study of Pebble Beds for reactor design 41

B.3. Motivation for a new pebble bed model 43

B.4. Improving the design of the reactor by means of Pebble Bed study . . 43

C. THEORY OF PEBBLE FLOW **45**

C.1. Granular fluid 45

C.2. State of the art: theoretical models 48

C.2.1. Discrete Element Methods (D.E.M.) 49

C.2.2. Kinematic Models 49

C.2.3. Stochastic Kinematic Models 50

C.2.4. Modeling a pebble bed for discrete simulations 50

C.2.5. Continuum dynamics approach: 51

C.3. State of the art: Experiments 53

C.3.1. AVR experiments 54

C.3.2. Australia 55

C.3.3. THTR-300 56

C.3.4. ANABEK-Experiments 57

C.3.5. MIT 58

C.3.6. China HTR-10 60

C.4. Other applications in the industry: silo theory, flow zones and pressure distribution 60

C.5. Conclusions of experimental results 62

C.5.1. Problems found in the access to information and data 63

D. FLOW MODEL DEVELOPMENT **64**

D.1. Description of the problem case 64

D.2. Validity and theory of continuum approach 66

D.3. Coupling variables 68

D.3.1. Physical variables 69

D.3.2. Material Properties 71

D.3.3. Geometry and operation characteristics 73

D.4. Boundary conditions 74

D.4.1. Inlet/Outlet 74

D.4.2. Wall boundaries 75

E. SOLUTION TO THE FLOW PROBLEM **77**

E.1. Modeling ANABEK experiment 77

E.1.1. Modeling procedure 77

E.1.1.1. Obtaining a shear stress profile from ANABEK experiments 79

E.2. Computational solution 81

E.2.1. Particle Tracking as a technical solution 81

E.3. Geometry and material characteristics 84

E.3.1. Resume of ANABEK flow experiment 84

E.3.2. Resume of HTR-300 85

E.3.3. Material properties 86

E.4. Miscellaneous 87

E.4.1. Residence time distribution calculation method 87

F. RESULTS **90**

F.1. Introduction 90

F.2. Validity of the assumptions and parameters chosen 90

F.2.1. Saturation of the viscosity 90

F.2.2. Validity of the boundaries 92

F.2.2.1. Inlet/Outlet boundary condition 92

F.2.2.2. Wall boundary condition 93

F.3. Results of the flow simulations 98

F.3.1. Streamlines and flow characteristics 98

F.3.2. Residence time distribution 100

F.3.2.1. ANABEK simulations at hopper 101

F.3.2.2. RTD at core wall 102

F.3.2.3. RTD at top pebble bed surface 104

F.4. Validation of the results 105

F.4.1. Residence Time Distribution 106

F.4.2. Velocity profiles and streamlines 109

G. CONCLUSIONS AND OUTLOOK **110**

G.1. Conclusions of the pebble bed study 110

G.2. Outlook 111

Bibliography **112**

Índice de cuadros

3.1. Comparativa entre el sistema discreto y continuo 27

Índice de figuras

B.1. Design of a IV generation reactor included in the PBMR project. [Bazant et al. 2004] . . . 44

C.1. Horizontal pressure distribution over the core reflector. Comparison of different pressure models [Bedenig et al. 1968] . . . 46

C.2. Bridging causes a flow blockage in a conical hopper [NN 4] . . . 47

C.3. Hexagonal Close Packing of spherical particles. Arise maximum compacting possible . . . 48

C.4. Forces between pebbles [NN 1] . . . 49

C.5. Construction of an ordered pebble bed for a D.E.M analysis [Ooms 2008] . . . 50

C.6. The Five-Channel method for calculating the velocity of the flow . . . 52

C.7. Top view from of the empty AVR core reactor . . . 54

C.8. Geometry of the AVR reactor and the two core regions . . . 55

C.9. PVC core half-model [Bazant et al. 2004] . . . 59

C.10. Different granular flow types . . . 61

D.1. Inelastic collisions between solid grains [Frank 2009] . . . 67

D.2. Void fraction in reactor core [Ooms 2008] . . . 69

D.3. Stress transmission in a pebble bed [NN 2] . . . 70

D.4. Viscosity models . . . 71

D.5. Pressure at reflector for different values of wall friction coefficient . . . 72

D.6. Pressure at reflector for different packing factor values . . . 72

D.7. Force diagram over the core reflector . . . 75

E.1. Maximum shear stress values over the cylindrical reflector core for different viscosity values. No-slip boundary condition fixed 78

E.2. Horizontal pressures over the core reflector with ceramic spheres in ANABEK compared with Janssen's profiles for different friction coefficients 79

E.3. Horizontal pressures over the core reflector with graphite spheres in ANABEK compared with Janssen's profiles for different friction coefficients 80

E.4. Different stress profiles tried in the simulations 81

E.5. Lagrangian vs. Eulerian problem flow modeling [Frank 2009] 82

E.6. Comparison between Lagrangian and Eulerian flow models [Ma and Srinivasa 2008] 82

E.7. Visualization of tracking particles for the study of different core regions 83

E.8. Time already traveled by the marked fluid while the solver is calculating 84

E.9. Geometry of ANABEK model experiment 85

E.10. Geometry of THTR-300 core reactor 86

E.11. TRISO fuel pebble [NN 3] 87

E.12. Residence time distribution for core wall simulations. The slope and the center of the curve are used for calibration of flow model 89

F.1. THTR-300 Vertical velocity profile for different viscosity values at core height 4 m 91

F.2. THTR-300 Vertical velocity profile for different viscosity values at core height 0.5 m 91

F.3. Streamlines for different Inlet boundary conditions 93

F.4. Vertical velocity for different shear stress profiles at core height 150 cm 94

F.5. Vertical velocity for different shear stress profiles at height 50 cm . . 95

F.6. Vertical velocity for different shear stress profiles at height 15 cm . . 96

F.7. Vertical velocity for different shear stress profiles at Radius 10 cm . . 96

F.8. Vertical velocity for different shear stress profiles at Radius 24cm . . 97

F.9. Streamlines comparison for different material viscosities. Relative pressure boundary condition at inlet 98

F.10. Comparison between THTR-300 model experiment and simulation results for different viscosities [Bedenig 1966] 99

F.11. Vertical velocity contour-plot. Danger of stagnant flow in low velocity regions 100

F.12. Injection of tracking particles in ANABEK core model 101

F.13. RTD in the hopper for different wall shear stress profiles in the boundary conditions 102

F.14. RTD for different shear stress profiles 103

F.15. RTD for different shear stress profiles. Injection of a tracking particle layer over the core surface 104

F.16. RTD for different shear stress values. Two different profiles are tested 105

F.17. Scheme with the shear stress profiles. Step profile at cylindrical part and hopper 500 Pa linear profile 106

F.18. RTD at hopper. Comparison of the study case with D.E.M. simulations and ANABEK 106

F.19. RTD at core wall. Comparison of the study case with D.E.M. simulations and ANABEK 107

F.20. RTD at surface core center and 2/3D. Comparison of the study case with D.E.M. simulations and ANABEK 108

F.21. RTD curves comparison of the best case with D.E.M simulations and experimental data 109

Parte I

MEMORIA

Capítulo 1

INTRODUCCIÓN

1.1. Motivación

Desde los inicios del siglo XX la gran disponibilidad de recursos energéticos ha permitido un gran desarrollo económico y social. Sin embargo, esta situación ha cambiado. Por un lado las reservas de combustibles fósiles empiezan a mostrar signos de agotamiento siendo cada vez más difíciles de explotar. Por otro lado, hay una necesidad de reducción de las emisiones de CO2 a la atmósfera. Estos hechos, sumados a una demanda energética creciente, requieren de una apuesta por políticas a nivel global que lleven a un menor consumo energético, a mejoras de los sistemas productivos y de distribución, así como de una sustitución de las fuentes basadas en combustibles fósiles. Ante esta nueva situación, la energía nuclear juega un papel importante teniendo en cuenta las grandes cantidades de energía que es capaz de producir sin emisiones a la atmósfera.

El desarrollo de las tecnologías nucleares no está exento sin embargo de riesgos. Los últimos acontecimientos acaecidos en Fukushima nos recuerdan la indudable necesidad de incrementar constantemente los esfuerzos en seguridad. Para ello la investigación y la inversión son las maneras más fiables de producir energía limpia y sin repercusiones negativas para la sociedad. En este sentido avanzan los nuevos modelos de reactores, los de generación III+ que están siendo instalados en varios países, así como los futuros de IV generación cuyos modelos aún están en desarrollo.

Los reactores de IV generación tienen una diferencia fundamental con sus predecesores y es su capacidad de evacuar de modo pasivo el calor generado en el núcleo ante un fallo del sistema de refrigeración, llevándolo de este modo a una parada fría. Dentro de las diferentes tecnologías, los reactores de alta temperatura refrigerados por gas, con sus siglas "HTR" en inglés, son una de las apuestas más decididas para los futuros modelos de reactor. Estos reactores tienen una serie de diferencias respecto a los modelos más comunes refrigerados por agua, como los instalados en España, y es que en vez de ser refrigerados por agua, es un gas, generalmente helio, el encargado de evacuar el calor producido por la fisión de los núcleos de uranio o torio. Por otro lado, la moderación de los neutrones se lleva a cabo por medio de grafito y no por agua por lo que tenemos una ventaja al poder tratar por separado estas variables vitales para el funcionamiento del reactor nuclear. El uso de helio, a diferencia del agua, no supone un problema en cuanto a la contaminación radiactiva ya que el helio no puede ser transmutado en isótopos radiactivos, permitiendo además alcanzar temperaturas muy elevadas, en torno a los 950ºC, gracias al uso de materiales refractarios. Estas altas temperaturas ofrecen rendimientos muy altos a la hora de producir electricidad, y son así mismo una fuente valiosa como calor de proceso.

Dentro de la tecnología HTR los mayores esfuerzos se están realizando en el desarrollo de los reactores nucleares de lecho fluido, Pebble Bed Reactors en terminología inglesa, donde una vasija presurizada y con forma de silo cilíndrico es llenada con cientos de miles de esferas. Las esferas caen hacia abajo movidas únicamente por medio de la gravedad y la tasa de recirculación es controlado por un mecanismo de extracción.

Estas esferas pueden ser de dos tipos. O bien esferas de grafito puro cuya misión es la de actuar como moderador de neutrones en las reacciones nucleares así como de mejorar la eficiencia térmica del reactor, o bien, las esferas de combustible. Dichas esferas de combustible están compuestas por pequeñas partículas de uranio o torio las cuales están recubiertas de diferentes compuestos que evitan la difusión de los átomos radiactivos. Estas pequeñas estructuras se encuentran embebidas en una matriz de grafito de 6 cm de diámetro. Las reacciones nucleares tienen lugar en el interior de las estructuras anteriormente mencionadas, por lo que el movimiento de las esferas de grafito repercute en el desarrollo de las reacciones nucleares.

1.2. Objetivos

El movimiento de las esferas dentro de la vasija no es uniforme. Como consecuencia, el tiempo que tarda una esfera en recorrer el núcleo es variable. Por esta razón, es necesario adaptar la concentración de los materiales fisibles de cada esfera según la región del núcleo en el que son situadas. Así pues, es necesario ser capaces de predecir la velocidad a la que se mueven las esferas y para ello hay que comprender las fuerzas que gobiernan el movimiento del sistema.

Los objetivos de este proyecto se dividen en dos grupos:

En primer lugar, se requiere la compresión de los fenómenos físicos que rigen el movimiento en el seno de un lecho fluido. Con ello se debe construir un modelo en base a la experiencia recogida hasta el momento presente, dicho modelo ha de ser capaz de predecir las siguientes características del flujo.

- Líneas de corriente
- Perfiles de velocidad
- Distribución de los tiempos de residencia

Aparte del conocimiento de la física del problema, es necesario también cumplir unos requerimientos técnicos, ya que el presente proyecto esta ideado para una fase de pre-diseño, lo cual exige que sea posible la variación de numerosos parámetros y que el tiempo y capacidad computacional requeridos para realizar los cálculos sea razonable y no sea mayor de 1 día para un solo procesador.

Los datos obtenidos, serán comparados y en caso de ser posible, validados a través de los experimentos realizados hasta la fecha. Sin embargo, la confiabilidad de algunas de estas pruebas fue puesta en duda por la falta de documentación o por no coincidir los resultados obtenidos con lo reflejado en la documentación. Por este motivo, algunos de estos estudios y tras la consulta con diversos investigadores tuvieron que ser rechazados.

1.3. Organización de la memoria

El presente proyecto fue redactado originalmente en inglés y está incluido en el segundo volumen como anexo I. Sin embargo, al ser necesaria la traducción al castellano se ha organizado de la siguiente manera: la parte I corresponde a la memoria y se estructura con una breve introducción que explica los fundamentos de la tecnología de reactores nucleares HTR junto a las razones que hacen necesario el desarrollo de un modelo para lechos fluidos, así como de los objetivos a alcanzar; en el siguiente capítulo se hace un repaso a las tareas desarrolladas por el autor hasta la consecución de las metas propuestas, prosiguiendo con un apartado que resume los aspectos teóricos y el modelo desarrollado así como el estado del arte; tras este capítulo se muestran algunos de los resultados más significativos para finalizar con las conclusiones alcanzadas y una serie de propuestas para el futuro.

Esta memoria trata de resumir de un modo más simplificado todos los aspectos trabajados a lo largo del proyecto quedando a disposición del lector el trabajo completo en su versión inglesa en el anexo. Dada la necesidad de resumir todo el trabajo en un espacio pequeño se ha decidido referenciar imágenes y gráficas a dicho anexo. Toda la bibliografía consultada se encuentra también en su versión original ya que se entendió que de este modo queda una estructura de documento más consistente.

Capítulo 2

TAREAS DESARROLLADAS

El presente proyecto fin de carrera fue desarrollado dentro del Instituto de Seguridad y Tecnología Nuclear de la RWTH Uuniversity de Aachen y en colaboración con el Instituto de Investigaciones Climáticas y Energéticas del centro de Investigación de Jülich, ambos en Alemania. Fue realizado como parte de un proyecto global en el que se están desarrollando los reactores nucleares de lecho fluido para su uso comercial. Las tareas encomendadas al autor del presente proyecto son resumidas en:

- Investigación y búsqueda de literatura e información acerca de las investigaciones desarrolladas en el pasado. Para ello fue necesaria una búsqueda intensiva en las bibliotecas disponibles, así como el uso de bases de datos y las peticiones a diversas empresas. Algunas de las cuales, ya no existían como tales lo cual complicó y alargó esta fase del proyecto. La búsqueda de nueva documentación se prolongó hasta las últimas fases de redacción de la memoria.
- Preparación y asimilación de los diversos conceptos teóricos.
- Aprendizaje de las diversas herramientas informáticas. Dentro de los cuales se destaca CFX Ansys.
- Proposición de diferentes soluciones teóricas para la consecución de un modelo de cálculo que pudiera cumplir con los objetivos propuestos. Para ello se partió de los modelos existentes.
- Desarrollo de los métodos y búsqueda de herramientas, así como estudio de los parámetros más adecuados.
- Análisis y estudio de los datos obtenidos. Validación de los resultados comparándolos con los datos disponibles.
- Documentación del trabajo realizado y organización de los datos y resultados obtenidos.
- Realización de presentaciones e informes periódicos a los tutores, al catedrático del departamento y al resto de compañeros.

Capítulo 3

FUNDAMENTOS TEÓRICOS

3.1. Teoría de lechos fluidizados

El movimiento de materiales granulares en la vasija del reactor es similar a la descarga de un silo o al movimiento de materiales granulares en un conducto. A través del estudio de la teoría, la cual se encuentra más desarrollada en el capítulo 3 del anexo I, se destacan las principales características que desde el punto de vista teórico pueden ser resumidas como:

- Las fuerzas gravitatorias son las que originan el movimiento. En el tubo de descarga se encuentra un mecanismo que regula el número de esferas que abandonan el núcleo por unidad de tiempo. Por esta razón, la velocidad media de las esferas está sujeta a la restricción que le impone este dispositivo.

- Las fuerzas de fricción esfera-esfera están originadas por el contacto puntual entre ellas. La magnitud de dichas fuerzas es una incógnita dada la dificultad que existe para su medida. Sin embargo, parecen tener un rol secundario según la bibliografía consultada.

- Las fuerzas de fricción esfera-pared son las que tienen una mayor importancia en el desarrollo del lecho fluido. Las paredes del núcleo están formadas por materiales refractarios, generalmente grafito. A pesar de los bajos coeficientes de fricción del grafito, las presiones originadas por el propio peso de las esferas generan unas tensiones muy grandes en las paredes como demuestran los estudios realizados. Además, estas fuerzas son las causantes del perfil de tensiones que puede ser observado en la figura C.3.

- Fuerzas de larga distancia son aquellas cuyo origen y efecto se perciben en lugares distintos. Las fuerzas se transmiten mediante la interacción de esferas en el seno del flujo. En el caso de los reactores de lecho fluido, en las diversas referencias bibliográficas se determina que tienen un alcance de entre 5 y 6 diámetros de esfera. Se diferencian de su equivalente para fluidos viscosos en el alcance, siendo significativamente mayor para el caso de fluidos viscosos debido a la elasticidad de las colisiones entre moléculas.

- El fluido refrigerante se encarga de recoger el calor generado por las reacciones nucleares. Se trata de helio a alta presión que se hace circular desde la parte superior a la inferior. El efecto sobre el lecho de esferas se manifiesta en un incremento del peso del lecho debido a la perdida de presión del fluido al circular entre las esferas según ponen de manifiesto los experimentos realizados.

- Los lechos fluidos son sistemas discretos en los cuales, las propiedades de los elementos que lo forman pueden variar significativamente aun estando en localizaciones cercanas. Este hecho supone que en caso de un reactor pequeño compuesto por unas 100.000 esferas, nos enfrentemos ante un problema de análisis muy complejo siendo necesario analizar si es posible hacer una aproximación al continuo.

- La densidad del lecho fluido depende directamente del nivel de compactación de las esferas en el núcleo del reactor. Esta compactación es el resultado de dividir el volumen que ocupan las esferas realmente y el volumen total disponible. Los valores habituales están en torno a 0.62 frente a un máximo teórico de 0.74. Sin embargo, los valores no son constantes y junto a las paredes de la vasija presurizada, se registran oscilaciones muy fuertes. Estas variaciones influyen en la permeabilidad del lecho al paso del fluido refrigerante, pero también supone que la interacción entre las esferas será más violenta, lo cual genera más colisiones inelásticas y por ende mayor pérdida energética.

- La velocidad media de las esferas es muy baja, en rangos de 10^{-4} y 10^{-5}m/s dependiendo del modelo. Esta baja velocidad complica la realización de experimentos y genera un estado cuasi-estático en el cual es difícil saber con certeza si los coeficientes de fricción de las esferas son los estáticos o los dinámicos. Como clara ventaja, podemos aseverar tras los diversos estudios y observaciones el régimen laminar del flujo. Este aspecto permite simplificar el análisis y abre la puerta al estudio como si de un sistema continuo se tratase.

- La geometría es una variable que no es propia del sistema granular, Ahora bien, sus efectos sobre el mismo son tan importantes, que es imprescindible destacar su influencia. Todos los experimentos realizados muestran claramente el efecto que tiene una variación en la geometría. De hecho, la bibliografía consultada recomienda no escalar las dimensiones del reactor nuclear ya que no queda clara esta posibilidad.

3.2. Modelos teóricos

La teoría para el cálculo de lechos fluidizados se encuentra todavía sin un completo desarrollo. A modo de comparación, sería equivalente al estado de la mecánica de fluidos antes del descubrimiento de las ecuaciones de Navier-Stokes. Este hecho supone la necesidad de usar modelos basados en resultados empíricos y en el uso de modelos de cálculo.

Existen diversos métodos de cálculo que en su mayoría pertenecen a modelos discretos, los cuales tienen ventajas en cuanto a precisión de los resultados, aunque requieren de una gran capacidad de computación. Por otro lado se puede realizar una aproximación utilizando un sistema continuo. Expondremos los métodos más destacados, los cuales se encuentran ampliados en el capítulo C del anexo I.

3.2.1. Método de Elementos Discretos (D.E.M.)

Método desarrollado pro Cundall y Stack en 1979 y que es la base del estudio de dinámica molecular. Este método se basa en tomar uno a uno los elementos y en realizar los cálculos sobre todas las interacciones que tienen lugar en el seno del flujo de partículas. Al calcular para cada esfera y en cada paso de tiempo todas las ecuaciones de equilibrio de fuerzas se alcanza unos niveles de precisión muy altos. Por contra, en los cálculos realizados con el código PFC^{3D} para un reactor pequeño requirieron más de un mes de computación.

La mayoría de esfuerzos actuales van dedicados al desarrollo de métodos computacionales que permitan simplificar y acortar significativamente los cálculos. Sin embargo, los resultados obtenidos hasta la fecha muestran una gran precisión aunque para casos concretos. Además se enfrentan a otras dificultades como son la construcción del lecho de esferas y el modelado de las irregularidades que es posible encontrar en su seno.

3.2.2. Aproximación por dinámica de medios continuos

El movimiento de lechos fluidizados movidos por gravedad tiene un comportamiento macroscópico similar al de un fluido viscoso. Para ello se toman los valores medios de las variables de trabajo y se simplifican o anulan aquellas características propias de un sistema granular que no pueden ser modeladas por medio de un sistema continuo. Esta aproximación aplicada a reactores nucleares se inició en el Centro de Investigación de Jülich (Alemania) para el desarrollo del reactor THTR-300, que será usada como base para el presente proyecto.

Dicha aproximación permite mejorar la eficiencia de los métodos de cálculo ya que es posible utilizar el método de elementos finitos, disminuyendo significativamente el tiempo de cálculo a pesar de una perdida en el nivel de precisión. Se pierde también la posibilidad de estudio de las diferentes irregularidades que se pueden encontrar en el lecho de esferas, tales como la formación de cavidades, el fenómeno de "puenteado" (bridging en terminología inglesa) y efectos de cristalización. A pesar de ello, como hemos indicado en los objetivos, esta es la aproximación indicada para una fase de pre-diseño en la cual es más importante conocer el comportamiento general del lecho de esferas que las peculiaridades que podemos encontrar en localizaciones muy concretas.

3.3. Estado del arte: experimentos realizados

En esta sección se explicarán aquellos experimentos que tienen una mayor relevancia para el modelado del lecho de esferas y para su posterior comparación con los resultados de las simulaciones. En la sección C.3 del anexo I se puede encontrar un amplio resumen de los experimentos que fueron utilizados en el desarrollo de este proyecto.

3.3.1. AVR

El AVR (Arbeitsgemeinschaft Versuchreaktor por sus siglas en alemán) es el primer reactor experimental basado en el concepto de reactor nuclear de lecho de esferas refrigerado por gas. Fue construido en el Centro de Investigación de Jülich en la década de los sesenta. Diversos experimentos acerca del movimiento de las esferas se llevaron a cabo durante el tiempo que estuvo operativo. Para ello, se dividió el núcleo en dos regiones: externa e interna; y se introdujeron esferas con una carga de combustible nuclear mayor que las que estaban ya en el interior. De este modo, podían ser detectadas al salir por el tubo de descarga. Sin embargo, algunas de las esferas no fueron correctamente detectadas o lo fueron en el momento en el que se desmanteló el reactor ya que habían tardado más tiempo del previsto en recorrer el núcleo.

3.3.2. THTR-300

El reactor THTR-300 (Thorio High Temperature Reactor en sus siglas inglesas y de 300 MWe) construido en la ciudad de Hamm (Alemania) fue el primer prototipo comercial instalado en el mundo. En su interior no se realizaron experimentos, pese a lo cual, para su diseño se llevaron a cabo multitud de pruebas, entre las cuales hay que destacar los realizados en una maqueta a escala hecha de metacrilato en la cual se introdujeron esferas opacas y translúcidas en un medio líquido. Estas pruebas permitieron demostrar el régimen laminar del lecho fluidizado. Además se realizó un estudio acerca de la influencia que tiene el ángulo de la tolva sobre la evolución del flujo.

Una segunda serie de experimentos acerca del comportamiento del flujo de esferas consistieron en el estudio con maquetas a diversas escalas del THTR-300, introduciendo esferas marcadas y dejándolas recircular a un ritmo controlado por un mecanismo de expulsión. Lamentablemente, la escasa documentación encontrada sobre estos experimentos no permitió el uso de estos datos ya que su fiabilidad no pudo ser contrastada.

También se desarrolló el primer modelo computacional destinado al estudio del movimiento de esferas basado en un sistema continuo y resuelto con un método de elementos finitos. Como se indica anteriormente, este modelo es la base del presente proyecto.

En los informes de operación del THTR-300 se reportan algunas incidencias como: el atasco de algunas esferas, la ruptura de las mismas debida a impactos, la generación de polvo de grafito, así como la variabilidad de las condiciones de trabajo en el núcleo del reactor. Estos datos resultan importantes a la hora de delimitar las posibilidades de cálculo del presente modelo.

3.3.3. ANABEK

La serie de experimentos ANABEK (ANAlyse der BElastung des Kernaufbaus por sus siglas en alemán) fueron realizados en la década de los 90 por SIEMENS A.G. y consistieron en el estudio de un modelo a escala 1:6 del diseño de reactor nuclear HTR-M 200 en el cual se analizó la influencia que tiene el lecho de esferas sobre la estructura de la vasija y el comportamiento del flujo de esferas. Para ello se prepararon dos grupos diferentes de experimentos.

Por un lado se realizaron los análisis de tensiones en la vasija. Para ello, se introdujeron esferas en el modelo y se midieron las tensiones axiales y radiales sobre numerosos puntos de la vasija, las localizaciones exactas se encuentran en [Babilas 1992]. Se realizaron las pruebas con tres materiales diferentes. Grafito, plástico y un material cerámico dando como resultado distribuciones de presión similares pero de magnitud muy diferente.

La segunda parte de los experimentos analizó el comportamiento del flujo por medio de un estudio estadístico de los tiempos de residencia de las esferas en el núcleo y la influencia que tienen las diferentes regiones. Para su realización, se rellenó la vasija con esferitas de polímero plástico de 10.16 mm de diámetro, 1:6 de las reales, y se tomaron esferas marcadas de diferentes colores. Las zonas estudiadas fueron: tolva, paredes de la vasija, la región central, en un anillo a distancia intermedia y en toda la superficie superior del lecho de esferas. Para el análisis de cada región se introdujeron bolitas marcadas en las zonas de estudio. Según iban apareciendo por el conducto de expulsión se registraba el momento en el que abandonaban el núcleo. Estos experimentos se realizaron con el lecho en dos configuraciones diferentes: empaquetamiento aleatorio y compresión del lecho. Esto origina resultados diferentes por lo cual se ha de tener en cuenta el papel del factor de empaquetamiento y por ende de la densidad del lecho de esferas.

3.3.4. Teoría de Silos

Una de las áreas de estudio de los flujos granulares corresponde al estudio y análisis de los silos de almacenamiento. A pesar de que generalmente su objetivo es el diseño estructural de los silos, también estudian los diferentes patrones de flujo posibles con el objetivo de hacer que no existan zonas de estancamiento o de velocidad muy baja. Además el perfil de presiones generado por un material granular se explica a través del efecto Janssen, el cual consiste en la saturación del valor de presión una vez se ha alcanzado un cierto nivel de profundidad. Se ha desarrollado en China una expresión específicamente ideada para el cálculo de las presiones horizontales y verticales en los reactores de lecho fluidizado, ver ecuaciones C.9 y C.10 del anexo I. Esta circunstancia no permite sin embargo, explicar en qué modo se comporta la presión en el interior del silo una vez se ha pasado del nivel de saturación. Se conoce a través de los experimentos realizados, que esta presión tiende a decrecer ligeramente hasta la zona de transición entre la parte cilíndrica y la tolva, para luego disminuir bruscamente hasta cero en el orificio de salida. Sin embargo, no se conoce ninguna expresión que permita predecir un perfil similar. Ver figura C.1 del anexo I.

3.4. Desarrollo de un modelo fluido

3.4.1. Descripción del sistema granular

El número de variables que rigen la física del problema ascienden a más de veinte [Tingate 1974]. Dado que se pretende modelar el lecho granular por medio de un fluido viscoso, es necesario remarcar las diferencias más importantes que se han encontrado. En el capítulo D del anexo I se encuentra una descripción más detallada.

LECHO FLUIDIZADO	**FLUJO CONTINUO**
Flujo granular: mecánica de sólidos	Fluido viscoso: ecuaciones de Navier-Stokes
MEDIO NO CONTINUO	MEDIO CONTINUO
1. Es posible identificar partículas individuales 2. s distancia entre las caras →Colisiones inelásticas 3. Fuerzas normales y tangenciales al interaccionar esferas	1. No es posible la identificación de una partícula fluida 2. Se asumen colisiones inelásticas entre moléculas 3. Se asumen sólo fuerzas normales
Flujo intermitente de esferas	Se requiere un **flujo continuo**: el análisis transitorio complica la resolución
Las **fuerzas de fricción** tienen una gran importancia en el comportamiento del flujo	La **fricción viscosa** tiene poca importancia a bajas velocidades
Distribución de **presión no lineal**: perfil de presiones dependiente de H, D, μ, ρ	**Presión hidrostática** definida por $P_h = \rho \cdot g \cdot H$
Propiedades de los materiales heterogéneas debidos a los diferentes puntos de trabajo	**Propiedades de los materiales homogéneas** para simplificar los cálculos
Resultados no reproducibles debido a variaciones estadísticas	**Resultados macroscópicos reproducibles**

Cuadro 3.1: Comparativa entre el sistema discreto y continuo

3.4.2. Validez de la aproximación al continuo

El uso de un modelo de fluido viscoso permite, a pesar de las notables diferencias, aproximar con cierta precisión el flujo de esferas. La mayor diferencia entre ambos flujos se encuentra en el tipo de colisiones que se producen en los diferentes flujos [Haff 1983]. En caso de un fluido continuo prevalecen las colisiones elásticas debido a las interacciones moleculares que son de tipo Coulomb o responden a las ecuaciones de la mecánica cuántica, mientras que en el caso de esferas macroscópicas, se producen colisiones que suponen una gran pérdida de energía cinética.

Para que sea posible la aproximación por medio del continuo es necesario que en el caso granular las colisiones puedan ser consideradas aproximadamente elásticas, por ello el criterio que se establece es que s<<d siendo s la distancia entre las caras de las esferas y d el diámetro de las esferas. Para comprobar la validez de este parámetro se utiliza el factor de empaquetamiento, dado que representa la ordenación de las

esferas en el lecho. En los reactores el valor es en general 0,62 frente a un máximo de 0,74 por lo cual se acepta la hipótesis. La simplificación de la ecuación de Navier-Stokes para la conservación de la energía cinética permite que sólo sea necesaría la ecuacion de conservación de momento ya que asumimos un coeficiente de restitución igual a uno [Nedderman and Tuzun 1979].

Otra de las condiciones establecidas es que D/d > 1000, siendo D el diámetro del reactor y d el diámetro de las esferas. En este caso no se cumple ya que las esferas de combustible miden 6 cm de diámetro, lo cual exigiría un diámetro de la vasija mayor de 60 m, siendo 10 m el diámetro más grande de vasija construido. Sin embargo, es posible realizar esta aproximación dadas las bajas velocidades y el régimen claramente laminar del flujo [Bedenig et al. 1967, Tingate 1970, Bazant et al. 2004].

3.4.3. Acoplamiento de variables

Una vez claras las diferencias entre los sistemas y asumida la posibilidad de utilizar un modelo de fluido viscoso es preciso relacionar las variables de los diferentes sistemas. A este proceso de simplificación y correlación entre variables se le denomina en este trabajo acoplamiento. Para ello, diferenciamos las distintas variables y parámetros.

La gravedad es la causante del peso específico del lecho de esferas siendo dependiente de la densidad del empaquetamiento de esferas. Tomamos un valor medio, y a pesar de que puntualmente haya variaciones grandes del valor, lo multiplicamos por la densidad media de las esferas. Es importante una correcta medición del factor de empaquetamiento y de los cálculos de densidad. Una pequeña variación influye fuertemente en las presiones que se generan sobre la vasija del reactor.

La presión en caso del almacenamiento de materiales granulares es diferente a la que generan los fluidos viscosos, la cual es lineal y está sólo en función de la profundidad para un fluido imcompresible. Dado que en un lecho de esferas, las fuerzas de fricción son muy elevadas, estas juegan un papel fundamental creando una fuerza opuesta de tal magnitud que es capaz de compensar la generada por el propio peso de las esferas.

La viscosidad es el principal mecanismo de fricción de los fluidos viscosos, sin embargo, no existe ninguna equivalencia comparable con el caso de los lechos fluidizados ya que el origen físico de las fuerzas es totalmente diferente. En el caso de un fluido viscoso nos encontramos que la tensión tangencial generada por los esfuerzos viscosos es $\tau = \mu\frac{du}{dy}$,siendo μ la viscosidad dinámica, y cuyo valor es muy pequeño para valores bajos de velocidad. Por el contrario, en un lecho de esferas, la fricción será proporcional a la presión horizontal por el coeficiente de fricción. La deformación tangencial en comparación a la presión horizontal en el caso de un lecho fluidizado es varios órdenes de magnitud inferior, con lo cual no es posible acoplar el rozamiento de las esferas con las paredes del reactor y entre las esferas en el seno de lecho por medio de la viscosidad. Por ello es necesario cambiar el rol de la viscosidad.

3.4.4. Definición de las condiciones de contorno

La definición de las condiciones de contorno es esencial para la correcta obtención de soluciones al problema diferencial. Para el caso de lechos fluidos existen diversas opciones [Hui, Haff et al. 1984] que fueron estudiadas y simuladas para verificar su validez. En la presente memoria, sólo se especifican las condiciones que finalmente fueron empleadas quedando en el capítulo D del anexo I las otras opciones estudiadas.

Las condiciones de entrada y salida indican cómo es introducido y extraído el flujo en la geometría. Como parámetro de entrada se conoce la tasa de recirculación de las esferas de combustible. Con ella, se calcula el volumen de esferas que se extraen del núcleo por unidad de tiempo y se hace una aproximación de la velocidad media del lecho de esferas. Esta velocidad se transforma en flujo másico, ya que una velocidad normal como condición de entrada o salida causa perturbaciones en el flujo que no son realistas. Por otro lado, y dado que en el núcleo del reactor las esferas caen por gravedad y entre la entrada y salida sólo hay un cambio de presión debida a la pérdida de carga del gas refrigerante, se establece como condición de entrada una presión relativa y en la salida se establece el flujo másico.

Las condiciones de pared son las más importantes a la hora de modelar el problema. Como ya se ha señalado antes, la influencia de las fuerzas de fricción es muy grande, y concretamente el de la fricción de las esferas con las paredes de la vasija del reactor. Por ello se estudiaron diversas posibilidades teóricas como pared deslizante o velocidad cero en la pared. Sin embargo, en este caso, ninguna de ellas es aplicable al caso real. Teniendo en cuenta que la velocidad de las esferas sobre las paredes es muy difícil de medir y de que se dispone de datos experimentales precisos acerca de las presiones en las paredes, se hace la suposición de que la presión de rozamiento es equivalente a la presión horizontal multiplicada por el factor de rozamiento, ver ecuación D.4 del anexo I. Por esta razón, se entiende que el valor en sí mismo no es tan importante como la forma y evolución del perfil de presiones.

Dado que el flujo muestra una dispersión azimutal y radial muy baja [Bazant et al. 2004] se asume que la componente angular de la velocidad es muy baja y que las fuerzas resistivas creadas sobre la pared son mucho menores que las creadas en dirección del flujo. Por ello se asume una tensión cero en la dirección tangencial. En el caso de la tolva las presiones son menores como muestran los experimentos [Babilas 1992] y simplemente se procede a una descomposición geométrica de las fuerzas. En la zona de transición, la cual es una zona redondeada entre el cilindro y la tolva, no se conocen datos experimentales y su geometría dificulta la implementación de un perfil, por esta razón se fija una condición de deslizamiento para esta región.

Para la elección del perfil de presiones adecuado se utilizan la serie de experimentos ANABEK. Dado que el objetivo es buscar un modelo que pueda ser aplicado en diversos modelos, se toman los datos experimentales de las presiones horizontales y se comparan con los valores obtenidos a través de la fórmula de Janssen. Se comprueba que la predicción es correcta en la zona intermedia, sin embargo, no es así desde la zona media hasta la salida, dado que el perfil de Janssen es del tipo $P = K\rho g(1-e^{\frac{h}{K}})$. Donde P es la presión horizontal, rho es la densidad, g la aceleración de la gravedad, h la profundidad desde la superficie y K una constante dependiente de las propiedades de los materiales y de la geometría. Por ello, se decide realizar una interpolación directa de los resultados obtenidos para los experimentos realizados con esferas de plástico y grafito. Estos materiales son los más similares a los utilizados en el estudio del flujo.

3.4.5. Propiedades de los materiales

Se define un fluido llamado *fluido esférico* como material líquido y continuo que ha de comportarse de un modo similar al lecho de esferas en el interior del reactor nuclear. La definición de la densidad se hace de modo directo en función de la densidad de las esferas de combustible y del factor de empaquetamiento. El fluido es incompresible por definición y termodinámicamente estable.

La definición de la viscosidad según la idea sugerida por [Scherer 1989] es el uso de una *viscosidad virtual* y asumir que no es posible un acoplamiento directo con las fuerzas de fricción. Siguiendo esta idea se aplican los estudios realizados [Thompson and Grest 1991] en los cuales se demuestra que a partir de ciertos valores de deformación angular del fluido se produce su saturación, y esta permanece constante. Por tanto, si la deformación angular es constante, queda una función lineal entre la tensión tangencial y la viscosidad. Así pues es necesario fijar una de las variables y dado que el esfuerzo tangencial lo podemos obtener a través de los experimentos, resulta más simple el fijar el valor de la viscosidad y así poder implementar directamente el perfil de tensiones obtenido en los experimentos.

3.4.6. Geometría y condiciones de operación

La geometría tiene una importancia esencial en el comportamiento del flujo. Existen diversas dimensiones características que han de cumplirse para que el flujo se comporte de modo uniforme [Tingate 1974] como son el diámetro de la vasija, la altura, el diámetro del orificio de expulsión y el diámetro de las esferas. En la sección C.3.2 del anexo I se indican los valores que han de cumplirse.

La tolva merece por sí misma una referencia aparte, su influencia es muy grande ya que se produce un cambio severo en la dirección del flujo de esferas. Esto por si solo tiene una mayor influencia que las fuerzas de fricción en esta región, por ello, un correcto diseño de la vasija es requisito para un comportamiento óptimo del flujo en el interior de la misma.

Se entiende que todas las condiciones aplicadas durante las simulaciones del presente estudio son las que se encontrarían en un reactor operando en condiciones nominales y uniformes.

Capítulo 4

RESULTADOS

4.1. Introducción

Tras la implementación del modelo fluido en el software ANSYS CFX, se realizaron múltiples simulaciones para comprobar la validez de las simplificaciones realizadas, por otro lado, fue necesario el desarrollo de técnicas para la observación y el análisis de los flujos granulares las cuales se explican detalladamente en el capítulo E del anexo I y que suponen una ventaja para el diseñador.

Los resultados obtenidos son comparados con los datos experimentales para su validación. En esta memoria se incluye un resumen de los datos más relevante quedando disponibles en el capítulo F del anexo I el resto de resultados. Se simularon diversas geometrías en función de los datos disponibles.

4.2. Validez de las hipótesis

4.2.1. Validez de las simplificaciones

La saturación de la viscosidad, a partir de cierto nivel de tensión, impide el acoplamiento de esta variable con las tensiones tangenciales cuyo origen es la fricción en el lecho de esferas ya que nunca podrá ejercer una tensión equiparable a la real. Para comprobar esta propiedad se llevaron a cabo diversas simulaciones en las que se muestran sendos perfiles de velocidad calculados para el modelo THTR-300, ver sección F.2 del anexo I. Se eligen diferentes viscosidades y se simula el comportamiento del flujo bajo condiciones de contorno en las paredes de no deslizamiento. Para viscosidades a partir de 1 Pa s no existe apenas diferencia en la forma del perfil de velocidades. Por esta razón, el uso de una viscosidad virtual resulta aceptable.

También se estudia para diferentes viscosidades el valor de las tensiones verticales sobre las paredes del reactor con la geometría de ANABEK, ver sección E.1 del anexo

I. Dado que la condición de contorno sobre las paredes es de no deslizamiento, obtendremos el nivel de tensión máximo para esa configuración. Para valores pequeños de la viscosidad, la curva de tensiones cambia de pendiente, mientras que a partir de aproximadamente 1 Pa s, esta crece linealmente. Si analizamos estos resultados y los analizamos frente a la ecuación $\tau = \mu \frac{\partial v_x}{\partial y}$ se confirma la hipótesis mencionada en la sección 3.4.3.

Por tanto, y dado que los perfiles de presiones son conocidos, sólo es necesario elegir un valor de viscosidad para el cual sea posible introducir directamente estos datos de presiones. Como ejemplo, se elige una viscosidad de $1x10^8$ Pa s. Como comparación este valor es varios órdenes de magnitud que un fluido muy denso como el aceite pesado de 10 Pa s.

4.2.2. Validez de las condiciones de contorno

Se simularon diferentes condiciones de contorno de entrada/salida según las posibilidades que la literatura explica. Una condición de presión relativa en la entrada y una de flujo másico en la salida dan como resultado un comportamiento muy similar de las líneas de corriente al que se observó en los estudios visuales. Se realizan estas simulaciones con dos valores de viscosidad muy diferentes y los resultados muestran una variación relativamente pequeña para cambios de viscosidad muy grande, lo cual confirma las hipótesis anteriormente realizadas acerca de la viscosidad.

Las condiciones de contorno sobre las paredes juegan el papel más importante dentro de la definición del modelo. Esta hipótesis se confirma en todos los resultados de las simulaciones realizados y deja claro que una correcta definición de la misma es fundamental en el modelado del flujo granular.

Se realizan cuatro simulaciones diferentes con la geometría y la configuración de ANABEK, en ellas y bajo las mismas condiciones se estudian los perfiles de velocidad en diferentes regiones del núcleo para valores de tensión diferentes. Para ello se caracterizan 4 perfiles de tensión diferentes que pueden ser visualizados en el anexo I. El primer perfil es simplemente una condición de deslizamiento sobre las paredes del reactor. Esto supone un deslizamiento total del flujo y una tensión nula. Se define también un perfil obtenido por la expresión de Janssen con unos coeficientes de fricción razonables para las esferas de ANABEK, el siguiente es el denominado *Step Profile* que es una interpolación directa de la presión horizontal obtenida en los experimentos. Como ya se ha indicado los valores son una primera aproximación a lo esperable para las esferas de plástico que no fueron estudiadas en los experimentos de presión. Por último un perfil continuo de 4000 Pa que sería similar a una condición de no deslizamiento. En las figuras F.7 y F.8 del anexo I se muestran los perfiles de velocidad para distintos radios del reactor.

Podemos comprobar cómo va evolucionando el flujo conforme va descendiendo y el efecto que tiene la tolva sobre el mismo. Al llegar la zona de la tolva se aprecia una convergencia del flujo. En ambas figuras se comprueba como en la parte superior el flujo se desarrolla con una alta dependencia de las condiciones de pared, sin embargo, al llegar la tolva, esta dependencia desciende y convergen hacia los mismos valores de velocidad. Estos resultados dan una idea de la influencia geométrica que efectúa la tolva sobre el flujo, disminuyendo en esta región los esfuerzos de fricción. Como conclusión es necesario remarcar la importancia que tienen las condiciones de contorno sobre el flujo.

4.3. Resultados y validación de las simulaciones

4.3.1. Líneas de corriente y características del flujo

En la figura F.10 del anexo I se comparan los resultados de dichas pruebas visuales con los obtenidos en las simulaciones, la concordancia de los resultados con las pruebas visuales es buena. Se confirma el régimen laminar y se pueden comprobar las líneas de corriente rectas en la zona superior que se van curvando según se acercan a la tolva. Es también reseñable la baja difusión azimutal de las esferas. Este hecho es importante para la simulación por medios continuos ya que como se explicó anteriormente, el diámetro del reactor es menor de lo que se supone necesario para cumplir con las condiciones de adaptación al continuo.

En el análisis de las diferentes regiones de flujo comprobamos en la figura F.10 del anexo I la existencia de zonas de muy baja velocidad vertical. No se detectan zonas de flujo estancado, lo cual no sería posible en un fluido, sin embargo es necesario tener este factor en cuenta y optimizar el diseño para disminuir en la medida de lo posible este factor.

4.3.2. Distribución de tiempos de residencia

En la realización de experimentos para lechos de esferas el método más utilizado para el análisis de los flujos consiste en la inyección de esferas marcadas, llamadas TK, en las regiones objetivo del estudio y su posterior contabilización. Para obtener la distribución se define un intervalo i compuesto por p esferas y se cuentan las esferas marcadas extraídas en ese intervalo ($\triangle TK$). Cada paquete de esferas en el periodo i requiere de un tiempo $\triangle T_i$ sobre el total $\sum T$, que es el tiempo teórico en el que se recircularía totalmente el núcleo, hasta que han salido las esferas de ese paquete. Tras eso se representa gráficamente el porcentaje de esferas marcadas sobre el total ($\frac{\triangle TK_i}{\sum TK}$) en el periodo i. Separando cada periodo i en porciones temporales del 10 %, o en otra fracción para más resolución, sobre el total podemos representar el porcentaje de esferas marcadas que han salido dentro de un periodo i que corresponde a una décima parte del tiempo total de recirculación.

Como método más importante para la evaluación y calibración del modelo se utiliza éste análisis en comparación a los resultados de los experimentos de ANABEK, los cuales son explicados en la sección 3.3.3. . En los resultados, se incluyen los datos obtenidos por un método de elementos en diferencias [Niessen 2009], el cual se supone significativamente más preciso como hemos explicado anteriormente.

Dado que en el capítulo F del anexo I pueden encontrase todas las pruebas realizadas, se exponen aquí los mejores resultados obtenidos que corresponden al perfil de tensiones *Step profile 2000 Pa.*

En la tolva, figura F.13 de anexo I, podemos comprobar que las simulaciones son capaces de aproximar con cierta precisión los datos experimentales, en comparación a otros ensayos realizados con el modelo de cálculo. Se observa que a pesar de grandes cambios en el perfil de tensiones sobre las paredes, los resultados cambian sólo para una pequeña región del núcleo. Siendo por tanto menor la influencia de las fuerzas de fricción como se suponía previamente. Comparando los resultados con el método D.E.M. vemos que éste tampoco es capaz de lograr una gran precisión. Este hecho pone de manifiesto que para regiones críticas, el uso de un método discreto ofrece ventajas sobre la aproximación al continuo.

La siguiente región a estudio es la más próxima a las paredes del reactor. Los resultados muestran esta vez menos capacidad de predicción. Se realizaron numerosas pruebas con otros perfiles de tensión, con valores mucho mayores, las cuales eran capaces de predecir con bastante precisión los resultados sobre las paredes. Sin embargo cuando con esos mismos perfiles se analizaba todo el núcleo, los resultados se mostraban mucho peores. Si observamos la figura F.16 del anexo I en la que se analiza todo el núcleo del reactor, vemos que en este caso los resultados concuerdan muy bien con los resultados de las simulaciones. Por tanto el modelo es capaz de predecir el momento de salida para aproximadamente el 95 % de las esferas marcadas introducidas en la vasija.

Esta discordancia, teniendo en cuenta los supuestos teóricos previos, esta probablemente motivada por las diferencias propias de ambos sistemas físicos, y particularmente del alcance de las fuerzas a distancia. Es decir, podemos suponer que un lecho de esferas, la fricción producida por las esferas en contacto con la pared se transmite a menor distancia dado a la inelasticidad de los choques. Sin embargo, para el caso fluido esto no ocurre del mismo modo y su alcance es mayor.

4.3.3. Perfiles de velocidad

Dado que no existen datos con los cuales comparar las simulaciones realizadas, hemos de tomar los perfiles de las figuras F.7 y F.8 del anexo I como estimaciones que podemos esperar concuerden dado que tanto líneas de corriente, como la distribución de los tiempos de residencia son variables relacionadas unas con otras y ofrecen una buena aproximación a los datos experimentales.

Capítulo 5

CONCLUSIONES Y TRABAJO FUTURO

5.1. Conclusiones

El estudio de un lecho de esferas a través de una aproximación por medios continuos es una tarea compleja. Las diferencias físicas entre ambos sistemas son importantes y la creación de un modelo empírico está siempre condicionada por la información experimental disponible y la validez de la misma. Las conclusiones más importantes extraídas en el proyecto son las siguientes.

El gran número de variables existente en el marco discreto ha de ser reducido. Algunas de las diferencias propias de ambos sistemas serán una fuente de pérdida de precisión. Sin embargo, esto no implica una pérdida del sentido físico del problema, lo cual es imprescindible para definir un modelo robusto. Las condiciones de contorno del problema tienen la mayor importancia a la hora de desarrollar el modelo, destacando la condición de pared. Para un correcto acoplamiento de las variables es imprescindible caracterizar correctamente el efecto que tienen las fuerzas de fricción en el lecho de esferas y extrapolarlo al flujo viscoso.

La influencia de la viscosidad es mucho menor de lo esperado en un primer momento, pero concuerda con los supuestos teóricos. Lo cual explica, junto al origen tan diferente de las fuerzas, la imposibilidad de utilizar la viscosidad como variable equivalente a las fuerzas de fricción. Este hecho sumado a la confirmación de la saturación viscosa observada en las simulaciones permite el uso de una viscosidad virtual. El uso de esta variable es un avance respecto a las simulaciones anteriores ya que permite la implementación de perfiles de tensiones obtenidos por medio de experimentos o de simulaciones.

Las fuerzas a distancia han mostrado tener una influencia importante en el modelado. Este fenómeno permite explicar las diferencias en el comportamiento de ambos flujos. Condiciones de pared diferentes entre sí dan lugar a flujos que se aproximan muy bien. Por ello se supuso que la utilización de un fluido no Newtoniano podría mejorar esta situación. Sin embargo, no se encontraron evidencias en las simulaciones que demostraran esta suposición.

En la región superior de la vasija se puede observar un patrón de flujo másico, mientras que según se acerca a la zona de transición y la tolva se evoluciona hacia un flujo de embudo. Este hecho es consecuencia de una gran pérdida de energía en las paredes del reactor, lo cual puede derivar en zonas de estancamiento. Este hecho no puede ser detectado con un fluido viscoso, sin embargo, se encontraron regiones de muy baja velocidad que deben ser estudiadas en detalle.

El modelo sólo es capaz de predecir los valores medios en condiciones estáticas y homogéneas. Para el estudio de regiones concretas del núcleo del reactor se pierde precisión respecto a otros modelos de cálculo.

Se recomienda el análisis tridimensional para facilitar el estudio de regiones específicas aunque los resultados en modelos bidimensionales muestran un buen nivel de precisión.

El modelo fue utilizado con éxito en diversas configuraciones de reactor y de hecho está siendo utilizado actualmente como método de cálculo para el diseño de una variante del reactor HTR-M 200.

5.2. Trabajo futuro

Para el desarrollo del presente trabajo se utilizaron diversos experimentos como fuente de datos. Sin embargo, el acceso a los mismos resultó dificultoso y no estuvo exento de problemas. Por esta razón, sería conveniente la realización de una serie completa de experimentos que contemple tanto el análisis de las características mecánicas del lecho de esferas como el de su comportamiento fluido. Parte de estos estudios podrían ser confirmados con simulaciones para caracterizar mejor el comportamiento de las esferas y las interacciones con las paredes. La influencia de las diferentes regiones y de la geometría no está clara y por ello, sería conveniente realizar un estudio acerca de estas características.

No existe una formulación completa sobre la teoría de lechos fluidizados, existen modelos concretos como el del presente estudio pero que abarcan casos particulares y no siempre extrapolables a otras situaciones. Por ello, cualquier avance en este aspecto debería ser tenido en cuenta para futuros estudios.

Se realizaron simulaciones con diferentes modelos de fluidos como pseudoplásticos y fluidos de Bingham, sin embargo la falta de información experimental hizo rechazar esta posibilidad. Diversos campos en la mecánica de suelo han realizado estudios acerca de este tipo de comportamientos, sin embargo ninguno pudo ser aplicado. Se realizó una hipótesis acerca de un posible modelado de la viscosidad virtual a las variables del lecho de esferas. Esta posibilidad debe ser confirmada.

El uso de métodos combinados D.E.M. - F.E.M. está siendo desarrollado actualmente, es de esperar que este tipo de métodos permitan nuevas perspectivas de estudio, sin embargo, el análisis con fluidos viscosos se ha demostrado eficaz y eficiente.

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Proyecto Fin de Carrera

Estudio de lechos fluidizados de esferas aplicados a reactores nucleares HTR
(2/2)

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2011

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Parte II

“ANEXO I: ANALYSIS OF PEBBLE BEDS IN HIGH TEMPERATURE REACTORS”

Appendix A

INTRODUCTION

The future of energy production is at present one of the most important topics that concern the international community. The increase of oil prices is not only a temporary situation caused by a punctual event in the production. The already known reserves are probably at maximum exploitation capacity, also the political instability that affect countries where are placed more than a half of the world oil reserves requires the diversification of energy sources to ensure the future energy supplies. The use of other traditional fossil fuels such as natural gas and coal is also a problem due to the clear necessity of a global reduction in the CO2 emissions.

Nuclear technologies are present in this future outlook, but the associated risks that entails every technology and recent events that took place in Fukushima remind us the necessity of continuous research in safety features and improving the facilities that are running at present, replacing old plants for modern models and always looking after the safety as the most important priority, for that reason, the development of new reactor designs which are safer and more sustainable is required. In line with this is the current deployment of III+ Generation reactors and the development of future IV Generation designs. In this context High Temperature Reactors, also known as HTR, have an important role to play.

These reactors, which are cooled by gas instead of water, have several advantages in comparison with other reactor concepts. They are designed to resist coolant flow accidents by the use of heat resistant materials and passive heat removal technologies. An other advantage is the possibility of achieving high temperatures of the coolant flow, which allow better efficiencies in electricity generation and also offer the possibilities of heat process that have multiple utilities in industry.

An important part of HTR technologies involve the *Pebble Bed* reactor concept. HTR pebble bed nuclear reactors are conceptually simple, a pressured vessel filled up with spherical elements where the nuclear reaction take place and that are recirculated.

Different pebble bed reactors have been operated in the past. Two of these reactors are the AVR located at Jülich Research Center and the THTR-300 in Hamm both in Germany. Those facilities have given a lot of worthy experience but have also shown how even a simple concept has to face a lot of technological problems. Future projects all over the world, require new and more extensive knowledge about pebble beds to achieve the expected objectives in safety and efficiency.

For the design of the reactor vessel a pebble flow model is required. Different options are already available that can predict the flow behavior, but actually those solutions are not proper for an initial design stage, which is one of the requirements for the present project. This fact implies a flexible and low time consuming computational method.

In the present work, the study of the pebble movement inside the reactor vessel is carried out. After an extensive literature research and the study about granular flows behavior, the development of a pebble flow model was performed and simulated to check its validity.

Appendix B

MOTIVATION AND OBJECTIVES

B.1. Pebble Beds in the operation of nuclear reactors

Nuclear reactions are sustained by neutrons produced as a consequence of the chain reaction process, in pebble bed reactors the source of neutrons are the fuel pebbles which are moving during the operation of the reactor. Apart from fuel pebbles, and in order to control the nuclear reaction; graphite spheres, which have a neutron moderation role, are required. To ensure that the nuclear reaction behaves as expected, it is necessary that the neutron flux is controlled. Therefore, it is necessary to know how the pebbles move inside the core, because depending on the time that they take to travel across the vessel, a bigger concentration of nuclear fuel is required in each pebble. The concentration of the radioactive particles, the configuration of the pebble bed, location of the different spheres types, and the incoming pebbles are part of the fuel management tasks. Those task are essential for a safety and efficient operation of the reactor, and as it was previously explained the traveling time is required, but the measurement of this magnitude is not possible for a big number of spheres, hence, it is possible to obtain this time if the streamlines and the velocity profiles are known.

But not only the velocity has to be known; it is also necessary to make that every sphere introduced in the core leaves it within a defined time interval. For those reasons it is necessary the development of a calculation method for the pebble flow.

B.2. Objectives in the study of Pebble Beds for reactor design

In the study of pebble beds and granular flows the goals to be reached can differ radically depending on the area of research. In case of pebble beds applied to the design of nuclear reactors the knowledge of the dynamics and the movement of the particles in the fluid is the main objective.

The requirements of the present project are divided in two: physical and technical goals.

On one hand appear the comprehension of the flow behavior which is related with the physics of the problem and several mathematical solutions to it. The knowledge of the motion parameters for each single pebble could be desired in case of the analysis of small defined core regions, for example effect of control rods, but in fact, for an overall core design is enough to determine the relative velocities between pebbles and the trajectory which follow until they leave the core. That would be enough to characterize a pebble bed in the terms of the nuclear reaction and with the goals expected for the present work.

Therefore the main physical parameters in this study about Pebble Beds are:

- Residence time spectra
- Flow lines
- Velocity profiles

But the solution of this problem is not easy from a technical point of view due to the complexity of the system. A pebble bed behaves as a granular fluid where friction forces play a very important role. Taking into account that in this problem has to be faced with a huge number of variables, [Tingate 1974] specify more than 20, thus it comes necessary to precisely define the objectives and the parameters required at the present study. The interaction between pebbles and the core wall as well the forces between pebbles are difficult to be measured by means of experiments. In fact the experiments done in the past show clearly that experimental studies have a limited precision and they are time and cost intensive. The inherent physics and theory of granular flows is not yet fully developed and it is necessary to build models based on empirical data.

On the other hand the technical requirements that the model has to accomplish are:

- Flexibility
- Robust solution
- Limitation of calculation time and CPU capacity

The pebble flow model of this thesis is thought for a design stage, when many different possibilities and configurations of the reactor have to be studied. For that reason, the model has to be flexible enough to permit different configurations to be studied. This porpoise is not possible to be reached by means of experiments, hence seems to be more interesting the construction of a model. That model should define the constant parameters of the problem, those common characteristics of pebble beds, and allow the designer to change the geometry, operation points and material properties which would be definition parameters of the problem; but it is necessary also to define calibration parameters to adjust the results of the simulations. Another requirement is that the results of simulations can be obtained in a short period of time. That means that is not possible to run a code which gives a lot of precision but requires of a big amount of time. As an example, some previous test done with PFC^{3D} software needed of almost a month for a single case [Rycroft 2006]. This is not acceptable in the earlier stages of the design process.

B.3. Motivation for a new pebble bed model

In the early 60's began the first studies about the use of spherical fuel elements in pebble bed reactors. Since that moment, it was necessary to develop a calculation method of the pebble motion, despite all efforts, do not exist at the present moment any option that fulfill the requirements previously exposed.

The necessity of a flexible, low time consuming and reliable code seems possible with the features that nowadays computers and software can offer. In the development of a pebble bed model, two possibilities appear. One of the options is the approach done by molecular dynamics through difference element method codes (DEM). This method takes every single pebble inside the core into account and makes a force equilibrium analysis for every single sphere. A clear advantage of this method is the high precision of the results as it is shown by [Niessen 2009] and the possibility of studying the forces involved in the pebble bed. As a great disadvantage this method needs of a huge computation capability because for every time step, all those force equilibrium have to be solved.

The other option consists on approaching the pebble bed with a fluid model. Under this approach CFD codes give a great number of tools and possibilities to calculate the flow behavior. About that possibility exist some previous experience. A finite element method was developed and programmed in 1989 at Jülich Research Center [Scherer 1989]. Unfortunately this code is lost, however the related work is available and was used as basis for the present project.

In order to fulfill the objectives and to achieve them in the limited period of time that is available for this work, the analysis with a fluid model and the implementation to a commercial CFD software appeared as the most sensible option.

B.4. Improving the design of the reactor by means of Pebble Bed study

The operation of AVR and THTR-300 had to face some problems related to the pebble bed. Operation reports explained that pebble motion have a complex behavior that could not be predicted with previous models, because inside the reactor core there are regions where very different conditions are found [Kalinowski 2001, AVR 1990]. Also problems with pebble fracture and and dust must be solved in order to achieve a safe and well controlled reactor operation.

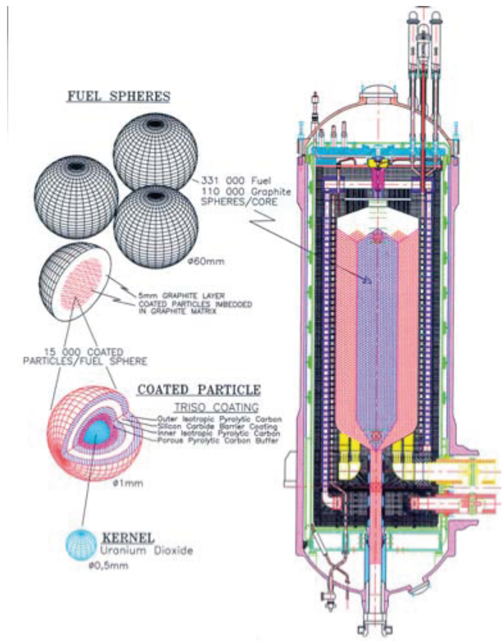

Figure B.1: Design of a IV generation reactor included in the PBMR project. [Bazant et al. 2004]

With a fluid analysis those facts can hardly been modeled, however it is necessary to develop designs which can minimize those negative effects, in order to do that, a smooth flow is desired, because impact forces and frictional effects between pebbles are reduced. As a conclusion, the optimization of the pebble bed reactor design is only affordable if the flow behavior, and all the devices, characteristics and geometries are properly understood.

Future designs like the one in figure B.1 have 2 different pebble regions which must remain without mixing in the time, therefore, the study of the pebble flow is necessary also o improve new designs and to improve the comprehension of its behavior.

Appendix C

THEORY OF PEBBLE FLOW

C.1. Granular fluid

Pebble movement in pebble bed reactors from a strictly physical point of view belongs to granular fluids whose main motion mechanism is gravity. These granular systems are in an early stage of research, comparable to the situation of Fluid Mechanics before Navier-Stokes equations were discovered. Due to its inherent physics complexity the possibilities of study are still limited by CPU computation capacity and the difficulties that takes to achieve a full knowledge from experiments about complex physical systems.The main characteristics of these kind of phenomena can be divided into forces which rule the behavior and problem specific issues. The main properties observed in pebble beds are:

Gravity is the main driving force, the vessel is placed vertical and the pebbles flow downwards. Although gravity is the main force of movement, the flow of pebbles is controlled by an exhaust mechanism which sets up the refueling rate, thus the pebbles cannot circulate freedom.

Friction forces have the main role in the flow behavior. The origin of these forces are divided between the pebble-pebble and wall-pebble friction forces.

Friction wall effects with core reflector are probably the main flow definition parameter. Their effects are remarked by the experiments and the theories about the influence that this effects has in the flow are the goal for many present studies. The core reflector of the reactor is coated with heat-resistant materials and they show a lower friction coefficient with pebbles than between pebbles themselves. Therefore the effects are much bigger and can be measured. It is also difficult to have accurately measurements of the friction forces present on the walls. The pebbles are 60 mm diameter, and their slow velocity makes the contact really punctual. Hence, the measure devices are not able to determine exactly the value of the pressure created. As a very important consequence of this forces, the pressure distribution all over the core is not linear, as it occurs with common fluids $P_h = \rho g H$, but it has a peculiar distribution which saturates at a certain level, in fact, in cores with a conical hopper, the pressure is reduced until almost 0 Pa in the surroundings of the outlet. See figure

C.1. The pressure magnitudes are comparable or even bigger that those originated by gravity.

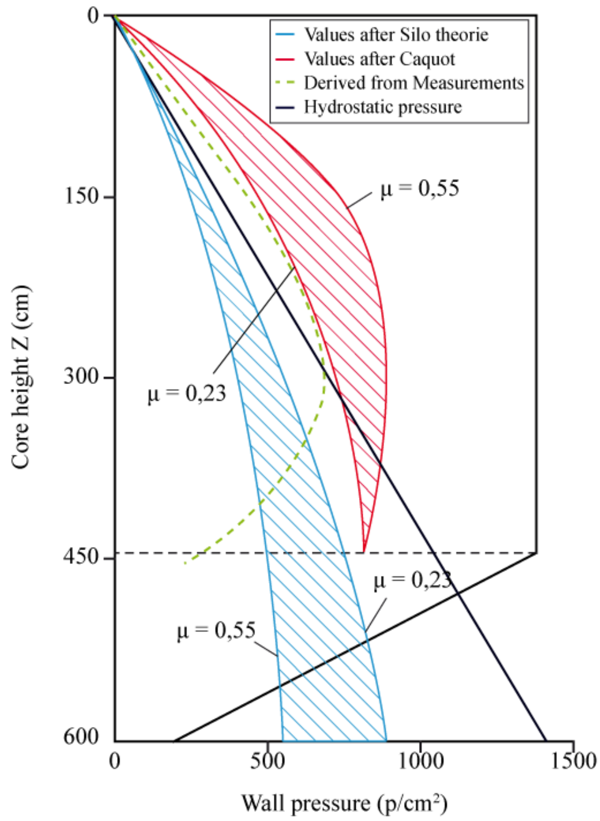

Figure C.1: Horizontal pressure distribution over the core reflector. Comparison of different pressure models [Bedenig et al. 1968]

Those effects are explained by the silo theory in section C.4. It is also necessary to explain that all the core reflector models have been designed with concavities all along the wall to avoid crystallization effects. The potential effect of this design on the overall friction forces is not clear, and supposed to have minor consequences [Tingate 1974].

Forces between pebbles are originated by the slip of pebbles within the flow. The value and characterization of this flow is not clear due to the impossibility of obtaining reliable experimental data. [Bazant et al. 2002] explain the importance of the force between pebbles is undefined and probably lower than gravity effect. Studies done in the past model the flow of grains with Couette flow models [Patton et al. 1987] but they do not clarify the explicit influence of pebble-pebble friction over the flow behavior and no conclusive information could be found. In case of pebble bed reactors appears an other problematic situation referred to the extremely low flow velocity, a fast circulation rate would be around 1 pebble min^{-1}, because in that case and taking into account the intermittent circulation, is not clear which parameter origin the forces, static or dynamic friction coefficients.

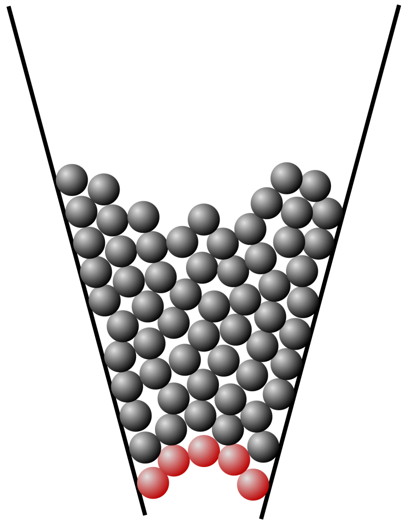

Figure C.2: Bridging causes a flow blockage in a conical hopper [NN 4]

Short-range forces involved in the flow behavior, these forces are produced by the physical contact between spheres, as an effect of the normal component and the tangential one on punctual contact. In case of pebble-pebble interaction there is an energy loss due to inelasticity.

Long-range forces are forces originated several diameters away from the location where the effect is detected. The transmission of this forces is related to the contact and collision of pebbles and the energy transmission related to them. [Bazant et al. 2002] consider that long range forces can be transmitted until 5 sphere diameters, but they are much more important for wall-pebble friction forces. Those facts were observed also in the results of flow experiments [Babilas 1992] and in the results of the present project in section F.3.2.

Coolant flow effects come from the loss of pressure in the flow of helium. In modern designs, the coolant gas is introduced from the top core and flows downwards to the bottom. The friction with the thousands of pebbles has an effect of decreasing the specific density of the pebble bed. It can be conclude, that no effect over the pebble flow can be appreciated [Gougar et al. 2004].

Discrete framework is a very important characteristic of pebble bed reactors. In fact it is not only that the flow is intermittently controlled through the exhaust mechanism, but also that as it was said, does not exist a continuous fluid or even a possible description on this way. Nevertheless, it can be observed that despite being a discrete system, the pebble motion behaves in some aspects like a continuous fluid. An important property was observed by [Bedenig 1971] in the first visual experiments done in Germany. It was possible to determine that the pebbles do not move randomly within the core. In fact they follow very clear flow lines with very low dispersion from the initial position. This statement made possible the development of pebble bed reactors and open the possibility of studying a complex discrete system with a continuum fluid formulation.

Pebble Packing Factor and granular structures have an undefined effect on the flow, but they are very important to the study of pebble bed in HTR reactors.

This measurement can be characterized by the packing factor which is the quotient between the volume occupied by the pebbles and the total volume; the maximum value is 0.74 given for hexagonal close packing (HCP) structure in figure C.3 whereas the average packing factor in a reactor it is about 0.64.

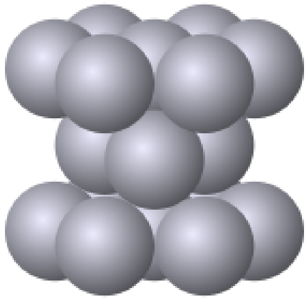

Figure C.3: Hexagonal Close Packing of spherical particles. Arise maximum compacting possible

In a whole core can be observed that the packing density varies a lot depending on the position that we study. The packing density determines the permeability of the bed and thus, the flow of the coolant gas helium which is the final responsible of the heat transported, and therefore of the output power. Test made by [Tingate 1973] show irregularities, also known as cavities, in the pebble structure that can be explain by combined effect of friction forces and the initial position when loading the reactor vessel. Bridging is a peculiar situation that happens in the outlet when it is too small, see figure C.2. Outlet diameters bigger that 5 pebble diameters avoid this situation [Bazant et al. 2004].

Low intermittent velocity has to be adapted to make possible the simulation of the flow by means of computational systems. As long as it is not possible to define an instant velocity in every position and moment, it is necessary to work with an average field of velocities. The low velocity has to be adapted in experiments and computational simulation, otherwise, the necessary time step in the computation process would make not feasible obtaining results.

Geometry is one of the most determinant variables that are involved in the pebble motion. Event it is not a particular characteristic of granular fluids, It is necessary to remark its importance and the consequences that has for the behavior of the system. It is fully explained in section D.3.3.

C.2. State of the art: theoretical models

The development of a general granular flow is the objective for many scientists at present. The application of these fluids is very common in engineering, medicine or chemistry; and the possibilities of a better comprehension of the phenomena can open many new applications. In the case of pebble bed reactors, the behavior of pebbles has a particular and important property. Despite pebbles are macroscopic elements which interact between them with complex and non-equilibrium relationships, gravity driven granular fluids having a common behavior. This important property allows us to model the behavior of a pebble bed without the necessity of a pebble by pebble study which is extremely complex and not necessary to fulfill the objectives of this thesis.

C.2.1. Discrete Element Methods (D.E.M.)

This numerical method was developed in 1979 by Cundall and Strack and it is the basis for Molecular dynamics and more recently, the behavior of granular flows in silos or fluidized beds. This method calculates the interaction of all the particles that are confined in a volume, as a difference with Finite Element Methods (FEM) where the volume is a continuum medium. For every single pebble and for every time-step all the force equilibrium equations have to be computed. This allows to study accurately the friction forces between pebbles and the interaction with all the surfaces. A study of [Niessen 2009] shows the high precision that can be achieved with this method. Nevertheless, and as a high inconvenient, appears the necessity of huge CPU time. In recent studies [Rycroft 2006] reports that for a 1E6 steps simulation in 60 modern processors more than 13h of computing time were required. At present, one of the research lines, consists on the improvement of the numerical method making it faster and more flexible. In order to do it, assumptions and simplifications of the model have to be made, but the problem is that in granular flow, do not appear general situations which can be simply neglected. Some of the methods are here remarked.

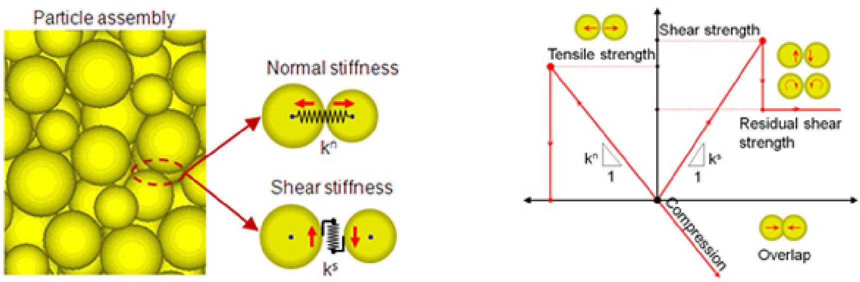

Figure C.4: Forces between pebbles [NN 1]

C.2.2. Kinematic Models

Kinematic models are based on the energy conservation law. Simple kinematic models are used to simulate granular fluids moved by gravity. Despite they are conceptually too simple compared with granular fluid physics; they have shown certainly good accuracy in the simulation results [Rycroft 2006]. However they do not explain the interactions between pebbles either with reflector walls.

C.2.3. Stochastic Kinematic Models

These models are an evolution of simple kinematic models and are based on statistical principles to explain the movement of pebbles. One of the methods is the Void methods [Mullins 1972] which involves the introduction of voids in the outlet of the core and flow up in the core. Then by means of statistics, the voids are dispersed in the core creating a distribution. This theory predicts properly the streamlines of the flow and also the key parameters if they are studied far enough from the walls of the core. Anyway, the theory does not explain the effect of the shear stresses over the reflector and their influence in the flow behavior.

An evolution of this method is the Spot Model. It was developed at the MIT (USA) . In this model the principles of the void movement are changed and it assumes a different way of void diffusion which explains better the movement of pebbles and the way how the occupy new spaces in the pebble bed. Their studies [Bazant et al. 2004] show that exist a longer diffusion length that it was expected. [Bazant et al. 2002] determine that the particles make an influence up to 10 pebble diameters.

At present the most recent studies are focus on different discrete models; they have better precision and go directly to the comprehension of the physical problem. In this thesis, the objectives do not cover all the granular fluids and it is necessary to simulate the pebble bed as a single unit, thus, the idea is to recover the first approaches done in the past my means of continuum dynamic models and improve them as much as possible.

C.2.4. Modeling a pebble bed for discrete simulations

D.E.M. methods and its different variants are capable to simulate the interaction of the pebbles and their movement, but they require of an initial situation in which the core is already filled of pebbles because those codes are not able to reach this first stage, the complexity is high as can be observed in figure C.5. This fact can appear trivial in a first sight, but it has a great importance and has to be properly prepared with the desired structure. The later dynamic simulations will be strongly influenced by the initial pebble bed structure.

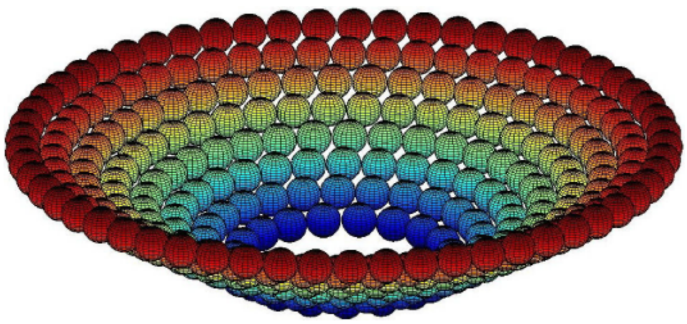

Figure C.5: Construction of an ordered pebble bed for a D.E.M analysis [Ooms 2008]

Studies done in the past [Tingate 1973] show the decisive influence of the initial packing bed structure to the later evolution of the flow, a random packing of pebbles has as consequence a lower packing rate which has advantages for the coolant gas flow. As a negative point is in such a structure, the density is not homogenous and it is not proper from a heat transfer point of view. The other option is to fill the vessel ordered with a pre-defined structure. It is interesting from a theoretical point of view, but in the practice, the situation may not be stable. In a series of experiments [Babilas 1991] used in this work as main reference, the pebbles are recirculated in different percentages of the core coming from an initial random packing situation. With the goal of measure the differences and how long does it take to reach a stable situation. Recent works done by the U.S. Department of Energy [Abderrafi et al. 2005] and in the T.U. Delft [Ooms 2008] propose different computation methods to fill a core with different possibilities

Most of the actual research lines are focus on the discrete approach, as long this is not the main approach of the present work, the author encourages a full revision of the literature about those methods in case of future studies based on discrete approach.

C.2.5. Continuum dynamics approach:

Gravity driven pebble bed framework shows a group behavior despite the fact that it is made by macroscopic particles. This property allows an intuitive approach to the problem. The pebble bed is considered as a fluid which can be done due to these long range pebble relationships. The first step was to visualize the flow behavior of packing pebbles. For that reason, were done a series of experiments [Bedenig 1966] in the Jülich Research Center (Germany) with glass spheres and color spheres. It was proved that the flow lines were very regular and straight, in fact can be ensure that we face to a laminar behavior. This important characteristic is necessary for a continuum approach, otherwise the solution of the equations would be much more complicated, making this approach useless.

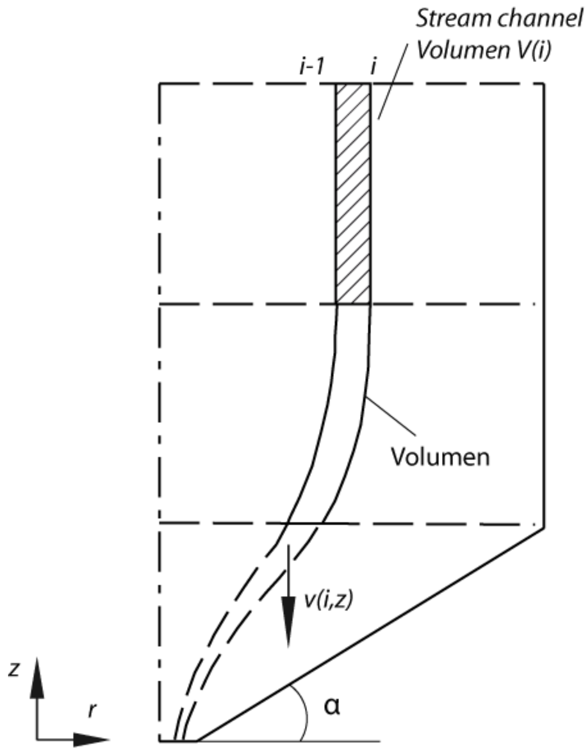

Figure C.6: The Five-Channel method for calculating the velocity of the flow

Taking this into account and after the glass spheres experiments; the first mathematical model developed for a pebble flow was done in Jülich Research Center [Bedenig 1967]. See figure C.6. In this model, the core from a frontal view, is divided in n canals. Then, from azimuthal view, the core is divided in the same number of rings, making then flow 3D canals. The velocity is calculated by means of mass conservation equations. This allows a simple way to make a simulation. The main problem of this model, is that needs the initial velocity at top of the core vessel and the travel time of the pebbles. That requires the experimental measurements and evidently they are time and cost intensive. Nevertheless it can calculate the shape of the flow lines, which accurate quite well to the experiment observations. This method either takes into account the interactions between pebbles and walls.

The next simulations were done in the early 80's for the design of the THTR-300 reactor prototype. The model was also in Jülich Research Center developed by [Scherer 1989] and it is one of the main theoretical supports of the present thesis. The procedure of equation simplification is here explained. The starting point are the Navier-Stokes equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{C.1}$$

$$\rho\frac{\partial v}{\partial t} + \rho v \cdot \nabla \cdot v = -\nabla \cdot P + \nabla\tau_{ik} + \rho f_m \tag{C.2}$$

$$\frac{\partial}{\partial t}(\rho e) + \nabla \cdot (\rho e v) = \nabla\tau' v + \rho g v \tag{C.3}$$

The model assumes incompressible flow $\nabla \cdot v = 0$ and stationary flow $\frac{dv}{dt}$, therefore is possible to linearized the equation.

The stress tensor:

$$\tau_{ik} = \xi \sigma_{ik} \frac{\partial v_i}{\partial x_i} + \eta(\frac{\partial v_i}{\partial xk} + \frac{\partial v_k}{\partial x_i}) \tag{C.4}$$

With incompressibility condition:

$$\tau_{ik} = \eta(\frac{\partial v_i}{\partial xk} + \frac{\partial v_k}{\partial x_i}) \tag{C.5}$$

Thus,

$$\rho \frac{\partial v}{\partial t} + \rho v \cdot \nabla \cdot v = -\nabla . P + \nabla \eta (\frac{\partial v_i}{\partial xk} + \frac{\partial v_k}{\partial x_i}) + \rho f_m \tag{C.6}$$

Introducing the stress tensor into the quantity of movement equation and if constant viscosity in a local area is supposed:

$\frac{\partial^2 v_k}{\partial x_i \partial x_k}$ Can be neglected

Then:

$$\rho \frac{\partial v}{\partial t} + \rho v_k \frac{\partial v_i}{\partial x_k} = -\frac{\partial P}{\partial x_i} + \nabla \eta \frac{\partial^2 v_k}{\partial x_i^2} + \rho g \tag{C.7}$$

Velocities in the problem are very low, therefore:

$$\rho \frac{\partial v}{\partial t} = -\nabla \cdot P + \eta \triangle v + \rho g \tag{C.8}$$

Equation C.2.5 is the linearized conservation of momentum equation. The solution was carried out by a F.E.M., however the complexity of this approach is to define the boundary conditions and all the domain characteristics.

C.3. State of the art: Experiments

Granular materials were studied from nineteenth century with the construction of the first silos for the storage of bulk materials. Recently the field of application for granular flow has increase exponentially. Nowadays many industrial and technical processes require a good knowledge of those materials and the laws that rule their movement in different scenarios. For that reason from the very beginning of the research, it became necessary to make experiments. Actually, most of the assumptions and models are based on empirical information and the experience achieved is very helpful in order to develop a general granular flow model. For these reasons, in this section the Experiments related to gravity driven pebble flows done until the present will be introduced. Also they will be briefly resumed to get a general idea of the methods used and finally they will be put together to extract the conclusions and assumptions that are the starting point for the development of this work.

C.3.1. AVR experiments

The AVR reactor (Arbeitsgemeinschaft Versuchsreaktor in German) was the first HTR pebble bed reactor built in the 60's at Jülich Research Center. AVR was a test nuclear facility where a lot of experiments were carried out to test the feasibility of the pebble bed concept.

Series of experiments were performed in the 80's introducing high-enriched uranium pebbles (HEU) in two different parts of the core, central and outer regions. In the moment of the pebble injection, the already placed pebbles were in an advanced stage of burn-up, therefore was possible to distinguish them in the outlet with a radiation detector [AVR 1990].

Figure C.7: Top view from of the empty AVR core reactor

In the first trial, 300 HEU pebbles were introduced in the central section of the core. In the second trial, the same procedure was done in the outer core, see figure C.8. Unfortunately not all the pebbles appeared in the expected time or were not properly detected. Some of them appeared years later when the reactor was decommissioned. With the information obtained, it was tried to improve the 5-Channel model using a new version with more canals, up to seven. See figure C.6. The results were not satisfying enough and the accuracy of the method was discussed as it is explained by the authors [Pohl 2009].

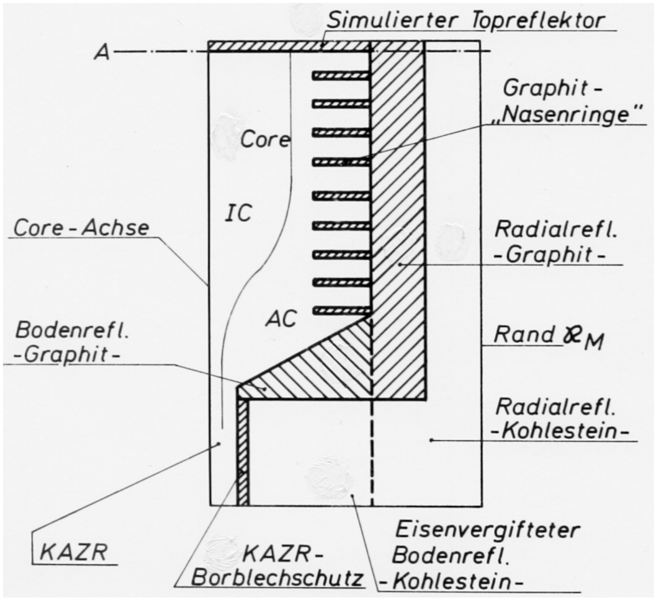

Figure C.8: Geometry of the AVR reactor and the two core regions

A visual inspection inside the reactor vessel which showed up an irregular distribution of the pebbles inside the core and the formation of small hills due to the location of the inlet tubes. This experience is not important from the pebble flow point of view, but it is interesting to understand that asymmetry in the pebble bed characteristics is common in pebble beds.

C.3.2. Australia

In 1970 a large research about the flow of pebbles took place in the laboratories of the Australian Atomic Energy Commission. The objective was to determine the influence of about 30 parameters [Tingate 1973] in the pebble bed behavior. All the details and the data from the experiments can be found in [Tingate 1970].

The experiments [Gatt 1977] were carried out in an aluminum cylinder with a conical discharge hopper. The angle of the hopper was variable and the vessel was filled with plastic pebbles coated with different friction properties materials. For the flow paths, radioactive pebble tracers were introduced in the pebble bed. With the help of gamma detectors was possible to measure the position in the 3 axes, the velocity was also measured, but the measurements were only able to predict if velocity increases or not and not a value.

The conclusions [Tingate 1974] of the experiment show that geometry plays a major role in the flow behavior:

- Relation between core height and diameter of the vessel H/D_v influence strongly the flow lines and the field of velocity homogeneity. For values bigger than 0.8 the flow is stable and has not more influence.
- The angle of the hopper and the transition hopper-cylinder affects directly to the residence times distribution and also affects directly to the size and shape of the flow patterns.
- The hopper by itself has a great influence over the flow evolution. This is caused by the abrupt change in the pebbles flow direction. The causes are not know and only a research about the best configuration is done.
- Relation between vessel and pebble diameter D_v/D_p is not problematic for values bigger than 50, but they are influence by the H/D_v ratio.
- Outlet to pebble diameter relation, D_{outlet}/D_{pebble} can cause blockages for values smaller than 5.
- High density decrease residence times in case on flat cores, but in case of H/D_v bigger than 1, there is not influence noticeable. In this conclusion the pressure loss of the coolant gas can affect the specific density of the bed.
- Friction coefficient has a major effect on the pebble flow but depends on the H/D_v rate.
- Multiple outlets and hoppers have a big effect, but has to be studied for every case

C.3.3. THTR-300

The reactor located in Hamm (Germany) was the first commercial prototype of HTR technology. A part of the research done for the design of this core reactor was carried out in Jülich Research Center. There, the knowledge acquired with the experiments done in the AVR experimental reactor which are compiled in a report [Pohl 2009], the test performed by Bedenig [Bedenig 1966, Bedenig et al. 1967] and the studies of the flow behavior [Langbein 1981] gave valuable information about pebble bed reactor operation.

Experiments done by Bedenig were carried out on scaled 1:2 and 1:6 models of the THTR-300 geometry. Those models were made of transparent plastic and filled with two types of spheres, glass and colored spheres. Then, the model was filled with a liquid which has the same refraction coefficient than the glass of the spheres. Using a special illumination method as can be observed in figure F.10, was possible to visualize the flow lines and to test the influence of different variables over the flow. The results showed interesting and determinant characteristics of the pebble flow. The flow lines were straight and symmetrical to the vertical axis with a curvature in the transition cylinder-hopper. This fact proves that if we think in the pebble flow as a common fluid, it would be under laminar regime. It was also observed low radial and angular diffusion of the pebbles and a very important issue of the pebble flow which is the possible existence of stagnant zones where the pebble velocity is zero or close to.

There are not experiments done directly on the THTR-300 and the validity of the results obtained in the visual experiments is not clear because the conditions of the experiment are very different to those expected in a pebble bed reactor.

However, interesting information was obtained about the operation of the reactor [Kalinowski 2001] and the mechanical and technological problems found. It is remarkable the production of graphite dust, the heterogeneity in the temperature distribution, also in the rupture of some pebbles during pebble circulation, changes in the coolant gas composition due to the filtration of oxygen and water steam in the circuit. All of those problems do not affect directly in the movement of pebbles, but they have an indirect consequence, that is the change of the friction coefficient making that with the same pebble coating material, different values of the friction coefficient can be found depending on the core position.

C.3.4. ANABEK-Experiments

The so called ANABEK experiments; "ANAlayse der BElastung des Kernaufbaus" in German; are a series of test done in the 90's by Siemens A.G. and Interatom GmbH. Three different pebble bed properties are determined. First it is tested the pressure distribution that the pebbles produce on the walls of the core for pebbles done of three different materials [Babilas 1991]. The second experiment [Babilas 1992] reproduces the effect of the temperature expansion that take place on the vessel during reactor operation, it is also tested how it affects to the pebble bed and how it reacts. The last one is a pebble flow test [Babilas 1992] of the different regions in the core.

Colored marked pebbles are introduced in defined parts of the core and then recirculated. The extracted pebbles are recognized by an optic detector and the time that they took to leave the core measured, with this information are draw up the residence time spectra. The scale of the model is 1:6, also for the pebbles which are 10.16 mm diameter. The circulation rate is much faster to make the time small enough: 1.28% of the Volume per hour, that is equivalent to 4600 spheres/h approx.

The experiments are carried out in a 24-side "cylindrical" core like it was supposed to be constructed the HTR-Module 200. Along the cylinder surface different strain sensors are placed, which can measure the pressures on the walls of the core in both axial and radial directions. The pebbles are made of four different materials. In the stress test they are made of graphite, ceramic material and plastic; and in the case of the flow analysis are done of polyacetat. The tests are done in static and in dynamic situation; this fact ensures that the measurements are not affected by random disposition of the pebbles.

In case of the pebble flow test; five different trials are performed. A defined number of colored pebbles are placed in separate positions to test the influence that the different parts of the core have over the pebble flow. A layer of pebbles is placed at hopper's height, in the top, one ring of pebbles is set touching the core wall, another ring of pebbles in the 2/3D from the center, also a group in the center of the core and finally a layer of pebbles over the whole core top surface, in figure E.9 the location of the test pebbles is shown, however the precise position is not explained exactly, which has to be taken into account for the data analysis due to high variability of experimental results.

From all the results, those which have interest for this thesis are the flow behavior of pebbles and the three tests to measure the pressure distribution on the walls. The conclusions that can be extracted from the tests confirm the laminar regime despite higher velocity rates, 20 times faster than in HTR-M 200 design. It can be observed also a low radial and angular dispersion but the most important results are the different residence times distribution of the different part. They show that in the central part the flow is very regular and cannot be found almost any influence from the walls or the friction with the outer core, in case of the 2/3D part the results is very similar and only in the outer core the difference is remarkable. In that position the friction forces are very high and the effect over the flow makes that the velocity lines are strongly deformed, for this reason can be explained the so spread residence time distribution. The hopper also shows a spread time distribution, this fact confirms the observations than in the past [Tingate 1973].

The stress tests have great interest, because they show that for the same geometry and changing only the materials of the pebbles, the friction and pressure distribution is strongly affected; not in the pressure distribution profile but in the values which is contradictory, as it was previously explained, with the Australian conclusions. About the profile it is the expected result under the formulas that are used in silo construction.

C.3.5. MIT

In the Massachusetts Institute of Technology (USA) took place the latest experiment related to the pebble flow. The work [Bazant et al. 2004] was a part of the PBMR project in South Africa and the objective of this test was obtaining empirical information for the later development of a mathematical model explained in section C.2.3. In the first part of the experiments are studied the flow lines, velocity profiles and the dependence with the hopper angle. In the second is studied a new feature that was supposed to be implemented in the PBMR. Instead of a core filled with a mix of fuel pebbles and moderator ones, in this new concept, was thought about the possibility of separating in a central column of graphite pebbles and an exterior ring of fuel pebbles. This idea aims to higher thermal efficiency due to better heat distribution. Therefore the pebbles may not mix while they are inside the core or at least only a couple of diameters from the initial location.

Figure C.9: PVC core half-model [Bazant et al. 2004]

The experiments were carried out in two different models. In figure C.9 is the PVC half-model of the core with a transparent glass dividing the cylinder in two parts that could be used for visual inspection and flow lines measurement. The second experiment is done in a 1:10 scale 3D model made of a PVC tube. The 3D model was built to check if the results obtained in the half-model could be valid or not due to radial dispersion of the pebbles. The models are filled with plastic pebbles.

As a difference with previous experiments, all the variables and properties of the materials were scaled base on a mathematical method; the scaled variables are height of the core and outlet, diameter of pebbles, velocity, wall effects and friction. The complexity of the real system does not allow to an exact conversion, also the difficulties of an accurate measurement make the task more complex, but some of the magnitudes can be neglected. To measure the flow paths of the pebbles, radioactive pebbles are used with a gamma ray detector which can follow the pebble in the three dimensions and able to calculate the velocity due to the capability of differential distance-time measurements. All the details about the experimental procedures and details can be found in [Bazant et al. 2002].

The results and conclusions of the experiments confirm most of the results previously obtained. The laminar regime is confirmed and the dispersion of the pebbles during the path is not bigger than two or three pebble diameters. Also the validity of the half model was confirmed by the gamma ray measurements; this fact can be useful in future tests. It seems that the velocity of the pebbles does not agree with the validation data given by the Security Commission of the PBMR, this fact is not strange because even the magnitudes are scaled, the validity of this transformation is not clear.

C.3.6. China HTR-10

In the present moment of this work, the HTR-10 is commissioned and operating but no experimental information or simulations have been found about the pebble flow in the Chinese reactor. Experiments about material properties and the flow behavior in two column granular flows were performed. [Xingtua and Shengyao 2009, Yu, Lu et al. 2010]

C.4. Other applications in the industry: silo theory, flow zones and pressure distribution

The research of granular flows started in the nineteenth century with the construction of the first storage silos. In that moment, they were built of wood and they could not reach high heights, but soon appeared problems such as explosions and the collapse of the silo structures. At the beginning was thought that inside a silo, the pressure distribution followed the hydrodynamic pressure law $P_h = \rho g H$, hence, the silo's structure were design to resist those loads. Soon, engineers realized with pressure test, that the distribution of pressures was not only dependent on the gravity force but also of the friction forces. These forces play a secondary or negligible role in common fluids in which the friction forces are ruled by viscosity, which is very small compared with the friction forces between solids.

Since the beginning of the twentieth century, many engineers worked on the phenomena that govern the pressure distribution of bulk materials. One of the most important formulations was developed by [Janssen 1895]. This formula is able to predict with low precision the pressures over the silo wall, although soon was proved that the formula was only valid for a very limited number of cases, the original idea was conserved and the formula was simply adapted. But there is not a general formula that can be used to calculate the pressure distribution for every bulk material. Instead of that, different materials or even same materials but with different dimensions or shape, require of different formulations. Recent studies done for the design of the HTR-10 in China [Yu, Lu et al. 2010] propose an expression to obtain the pressure distribution that fits properly well with the stress experiments carried out:

$$P_h = D\frac{\rho \cdot g - a}{4 \cdot \mu_{wall}}[1 - \exp(\frac{-4\mu_{wall} \cdot k \cdot z}{D})] \tag{C.9}$$

with k:

$$k = \frac{\sqrt{1 + \mu_{sphere}^2} - \mu_{sphere}}{\sqrt{1 + \mu_{sphere}^2} + \mu_{sphere}} \tag{C.10}$$

D	(m)	Core diameter
μ_{wall}	-	Friction coefficient pebble-wall
μ_{sphere}	-	Friction coefficient pebble-pebble
ρ	(kg/m^3)	Apparent density taking into account packing factor
a	(Pa/m)	Coolant pressure loss
g	(m/s^2)	Gravity acceleration constant
k	-	Relation between horizontal and vertical pressure components

The profile increases quickly until a saturation value, in which equilibrium of friction and gravitational forces is found, figure C.1. In the cylindrical (or squared) part of the silo this supposition is on accordance with the real situation. This situation remains constant until the transition cylinder-hopper comes, in that situation the profile becomes variable and with pressure peaks which can multiply the maximum pressure two or even three times [Ravenet 1992], but the pressure reduces until 0 Pa in the outlet, so most of the authors support that despite this pressure peaks, can be considered that pressure decreases from the saturation value to 0 Pa with a parabolic profile. Unfortunately the available data about the pressure distribution in this part of the silo cannot be used numerically and only as an estimation due to the low reliability of the measurements.

The hopper is the most important geometrical part of the core, and its design has to be carefully studied in order to have a smooth flow and without stagnant zones. In the figure C.10 is remarked the existence of dead zones and the influence that the angle of the hopper has on its side. All the experiments determine the optimal hopper angle about 30º and with central discharge [Tingate 1974]. In case of eccentric or multiple outlet discharge, the flow has an irregular structure and the analysis gets even more complicated.

The ideal core should have the flattest velocity profile possible, for this reason, the different flow zones have to be analyzed with the clear objective of the dead zone elimination and to obtain a smooth flow of pebbles, but it is not clear if it is possible to achieve that under all reactor conditions.

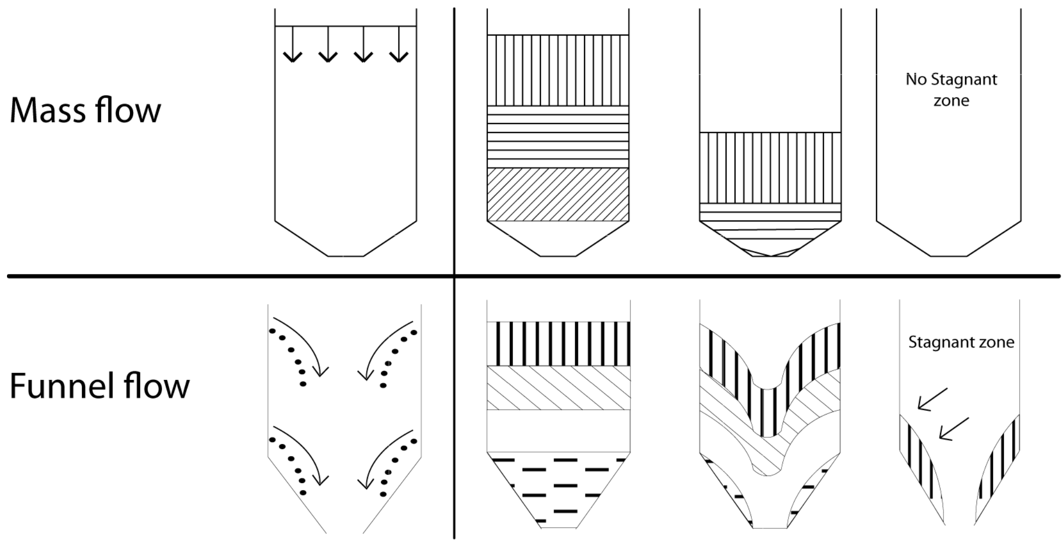

Figure C.10: Different granular flow types

Figure C.10 show the two basic flow types. In case of pebble bed reactors, the flow type is a mixture of both mechanism. In the upper part, they type is clearly mass flow, but as long as the flow crosses half of the core, it starts to be noticeable a change on the flow pattern.

C.5. Conclusions of experimental results

The experimental data provided by experiments has a great importance for the development of this work; the author considers very important that all the experiments are properly studied and understood for future development, nevertheless all the assumptions necessary have to be physically realistic and have to be proved by experiments. The insufficient documentation available about some of the previous explained trials and the possibility that contain measurements fails makes necessary to discard them in a validation process.

Under the different experiments previously explained and the theory about granular flows, we can ensure that these conditions are common for pebble flow in case of pebble bed reactors.

- Laminar regime
- Low radial and tangential dispersion. Possible 2D or symmetrical simulation
- Limited scale variable possibilities, thus necessary most precision possible when modeling simulation
- Discontinuous flow of pebbles can be approximated by mean values of variables
- Not only direct friction forces; long range forces play important role. Other characteristics such as adhesion of particles, clump rolling friction, arching cannot be modeled
- Possibility of viscous models to characterize the pebble bed properties but lack of experimental data.
- Coolant gas effects can be simplified by an increase/decrease of the mean viscosity value.
- Friction forces coefficient distribution for different parts of the core: Temperature, concentration of H2O, dust are the main distortion variables
- Geometry has a major role in the flow behavior. Remark the effect of the hopper and the transition cylinder-hopper.

C.5.1. Problems found in the access to information and data

Due to the specific problem and the non-conventional elements of study; the research task was hard and took more time than expected. It was also problematic to obtain the experimental data of some test because they are under industrial right laws and others were lost. This lack of information is the cause to reject some data because it was not possible to confirm all the details that were involved in the realization of the experiments. In the validation section will be remarked those test where some information deficiencies have been found.

Appendix D

FLOW MODEL DEVELOPMENT

D.1. Description of the problem case

No general governing equations for granular flows are available in the present moment, therefore the use of experiments, observations and simulations are required as starting point for the development of a model using a continuum fluid approach. In the previous chapter the most important differences between both systems have been exposed, but also it is a resume itself of the common characteristics that can be observed in pebble beds applied to nuclear reactors, and that allow to distinguish them from other granular flow types.

In order to guarantee that the physical meaning of the variables coupled is correct and after an extensive literature research and an analysis of the experiments explained in the previous sections; all the variables, parameters, characteristics, properties and observations are put together to have a simple overall view of the problems to solve.

The problem could be defined in simple terms as a cylindrical vessel which ends in a conical hopper and is filled with spheres which leave the core intermittently. But even in the ideal case, the description of the pebble motion through a common viscous fluid is very limited. The macroscopic behavior is similar in operation conditions but they respond to forces which are very different in origin, thus a direct transformation of the variables, parameters and scales is not acceptable. For these reasons it is necessary to couple the variables based on similar phenomena that can be experimentally demonstrated.

PEBBLE FLOW	**CONTINUUM VISCOUS FLUID**
Granular Flow: Molecular dynamics models. Solid mechanics equations	VISCOUS FLUID: Governed by Navier-Stokes equations
NON-CONTINUUM MEDIUM	CONTINUUM FRAMEWORK
1. Possible to identify a single particle of the fluid 2. s pebble face distance →inelastic collisions 3. Normal and tangential forces between pebbles involved → Force and momentum	1. Not possible to identify a single fluid particle 2. Assumption of the elastic collisions between molecules 3. Assumption of normal forces interaction
INTERMITTENT PEBBLE FLOW: A pebbles leaves the core within discrete time interval	CONTINUOUS FLOW REQUIRED: A transient analysis complicates the resolution and does not give more valuable information
FRICTION FORCES have major influence in the pebble bed behavior	FRICTION plays a minor role in the flow at very low velocities. Viscous forces are small at low velocities
NON LINEAR PRESSURE DISTRIBUTION: Pressure profile dependent on friction forces, cohesion and location of pebbles	HYDROSTATIC PRESSURE DISTRIBUTION which is determined by $P = \rho \cdot g \cdot H$
MECHANICAL PROBLEMS during the flow of pebbles: Crystallization, angle of repose, bridging and blocking which cause irregularities in the flow	HOMOGENEITY in the properties and structure of the fluid. Irregularities are not stable in time
HETEROGENEITY OF PROPERTIES within the fluid. The density of the pebble bed is variable in different in different locations	COMPRESSIBLE FLUID needed. Characterize the variation in the density involve much more complexity and does not give more information
HETEROGENEITY OF PROPERTIES: The friction coefficients in graphite are strongly influenced by atmosphere, temperature and material irregularities.	VISCOSITY MODELS allow different behavior patterns of the fluid
INITIAL PACKING of pebbles has a noticeable influence over the flow. Evolution to a stable situation	TWO-PHASE fluids are capable to experience heterogeneity in that way
MEASUREMENTS are difficult to be obtained. Necessary average values	EULERIAN approach does not allow to obtain information of a defined particle → Lagrangian approach
NON-REPRODUCIBILITY of results → Statistical mechanics required	Macroscopic reproducibility of results

Also some particular characteristics of pebble bed reactors must be taken into account.

CHARACTERISTICS	CONSEQUENCES
Pebbles of different diameters in some designs	Necessity of a two-phase fluid or approximation by a single fluid
Reactor not cylindrical, but n-side polygon	Angle corners and sharp regions difficult a smooth flow and create irregularities
Reactor walls with irregular texture to avoid crystallization	Walls are not flat and have roughness and cavities that affect the flow
Recirculation rate can be understood as mass flow	An average velocity can be an operation variable to calibrate the model
Spherical pebbles	No adhesion of grains, thus smoother flow but unknown viscosity model
Several devices like control rods and columns are introduced during the pebble motion	Effects over the pebble flow must be individually evaluated
Coolant flow	Changes in the specific density of the pebble flow
Extraction procedure of pebbles	A non careful extraction of pebbles can cause irregularities and rotational components in the flow[Gatt 1977]
Straight and regular flow lines. No azimuthal and angular diffusion	Laminar flow regime simplifies the resolution of the differential problem

D.2. Validity and theory of continuum approach

Despite the several remarkable differences between granular and continuum fluids, the use of a continuum fluid framework is useful to obtain simple, fast and feasible solutions to the problem, but this approach is not possible in every situation. [Haff 1983] did a research on the conditions that a granular flow has to fulfill to be described properly by a viscous fluid. He assets that the biggest difference between classical fluids and granular ones is the fact that in case of granular fluids, the collisions between particles are essentially inelastic, which means a strong loss of energy in form of heat, meanwhile in viscous fluids, the collisions take place between molecules and they can be considered as fundamentally elastic because in that situation, not only Coulomb forces between molecules have to be taken into account but also quantum mechanics.

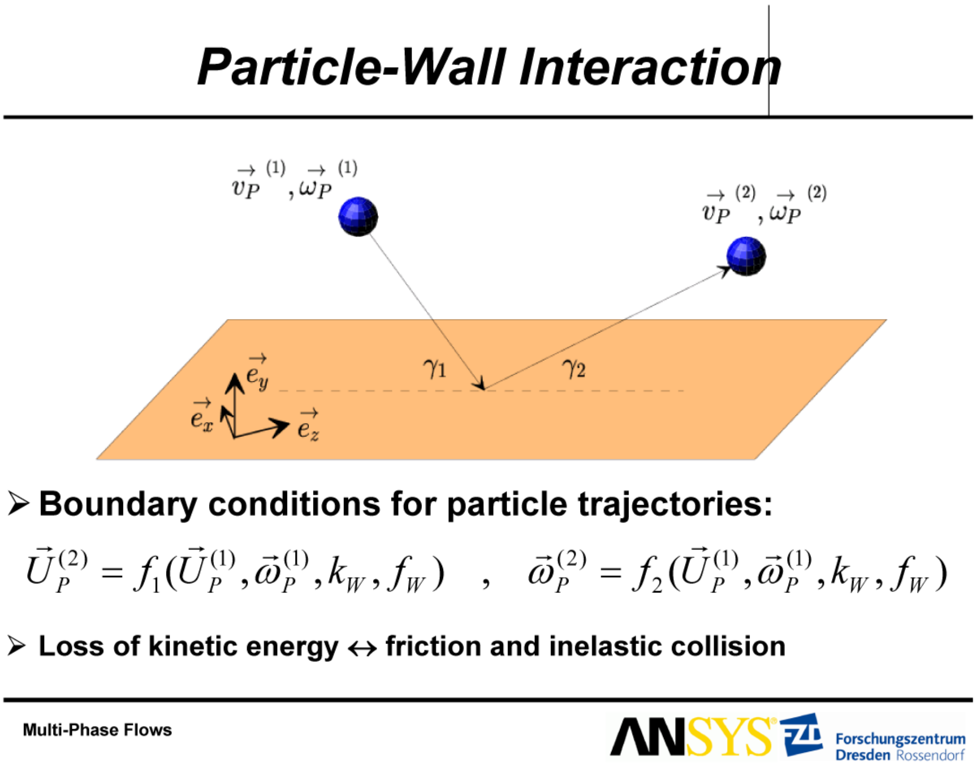

Figure D.1: Inelastic collisions between solid grains [Frank 2009]

This inelasticity of the system requires the usage of the equation of mass, conservation of momentum and energy; The Navier-Stokes set of equations is the basis of Kinetic Theory [Nedderman and Tuzun 1979]. In a packing of pebbles it is related with the distance s between the faces of the neighboring pebbles. The smaller is the distance, the less energy is lost and less inelasticity can be observed, the criteria set is s<<d where d is the diameter of the sphere.

The value of 0.61 for common reactors plus the low velocities of pebbles ensures that the inelasticity inherent to granular flows is small enough to consider the option of continuum approach.

The second condition required is that the quotient between the core diameter and the pebble diameter is bigger than 1000. That means, that in case of 60 mm pebbles, the core must be at least 60 m of diameter, then the biggest designs are in order of 10 m diameter. That condition is not fulfilled for HTR-Reactors but experimental data [Bedenig et al. 1967, Tingate 1970, Bazant et al. 2004] assets that the flow regime is clearly laminar and the particles follow in an uniform flow [Patton et al. 1987], therefore we assume that the low velocity and the ordered movement of pebbles is sufficient condition to use a continuum approach such as show the model developed by [Scherer 1989].

Once accepted the viability of the continuum framework approach it is necessary to simplify the Navier-Stokes set of equations. It is previously explained that mass, conservation of momentum of energy equations govern the flow in case of big energy dissipation fluids.

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{D.1}$$

Conservation of momentum simplified and linearized:

$$\rho \frac{\partial v}{\partial t} = -\nabla . P + \eta \Delta v + \rho g \tag{D.2}$$

And the equation of energy:

$$\frac{\partial}{\partial t}(\frac{1}{2}\rho u_i + \frac{1}{2}\rho \vec{v^2}) = -\frac{\partial}{\partial x_k}[\rho u_k(\frac{p}{\rho} + \frac{1}{2}u^2 + \frac{1}{2}v^2) - u_i \eta(\frac{\partial u_i}{\partial x_k} \vec{+} \frac{\partial u_k}{\partial x_i}) - \kappa \frac{\partial}{\partial x_k}\frac{1}{2}\rho \vec{v^2}] + \rho u_i g - 1 \tag{D.3}$$

But in fact the energy equation can be simplified because the term of dissipation can be assumed as very small compared with the other variables. [Haff, Hui et al. 1984] approximate the viscous dissipation term to $I = \gamma \cdot \rho \cdot \frac{\vec{v^3}}{s}$; where gamma is proportional to $1 - e^2$ and e the coefficient of restitution that we assume one because elastic collisions are supposed [Bazant et al. 2002]. For this reason in the present work only mass and momentum conservation equations are taken. Mass conservation is implicit to the pebble bed inside a reactor where constant density, thus packing factor too, and no leakages of mass or changes in the volume are coherently supposed. Therefore the stress tensor in the conservation of momentum equation must be defined, but in case of common fluids, the influence of frictional forces is significantly smaller than in case of granular flow [Hanes and Inman 1985], hence it is necessary to couple the variables that govern the friction effects in case of granular fluids and to find a correlation between them and the viscous term of the Navier-Stokes equation.

D.3. Coupling variables

Obtaining a meaningful model requires that the most influencing variables that govern the behavior in a pebble bed must have an equivalent variable which causes the same effect over the viscous fluid and with the same relative weight respect other variables; this process is the key point in the development of the model. In order to simplify the process of comprehension, the variables are divided into 3 different groups: Physical variables, material properties and problem operation characteristics.

D.3.1. Physical variables

Friction and gravitational forces are the main motion mechanism in case of fluids under gravitational influence, but despite that fact the origin of those forces is not the same as it is previously explained in Paragraph C.1. In case of **gravity** the specific weight per volume unit is the variable that controls the value of the force, for viscous fluids that is represented by density, which is dependent on temperature and pressure and it is defined as the quotient of a differential mass portion and the differential volume that it occupies. But this definition is not possible in case of a non-continuum framework like pebble beds. In that case, it is chosen an average value called packing factor or void fraction and it is dependence is more complex than in fluids including temperature, pressure, shape and roughness of the spheres, elasticity of the material, adhesion and the surrounding atmosphere.

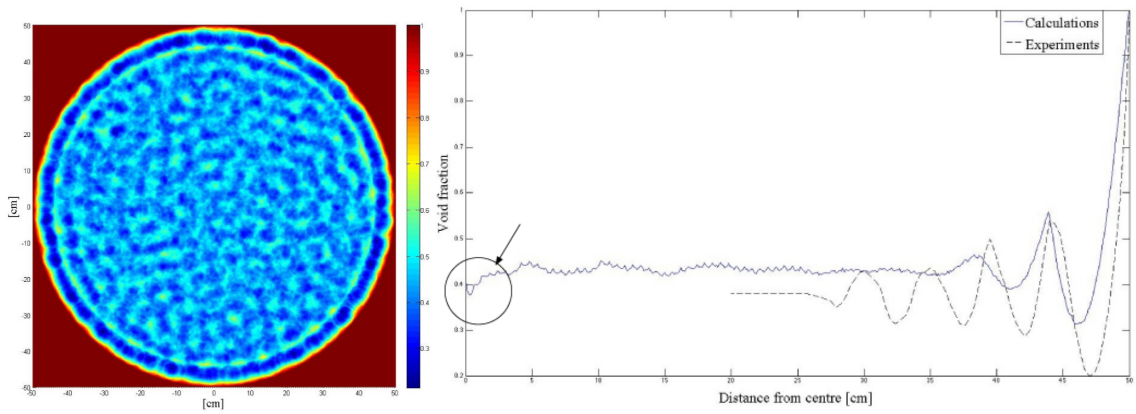

Figure D.2: Void fraction in reactor core [Ooms 2008]

In fact, these conditions are not constant during the reactor operation and as a consequence the value of the packing factor is neither constant. Specially in the areas closest to the reflector walls, this effect is amplified and it is related to the pressure distribution and friction effects [Ooms 2008] but this situation is found in a relative small area and for this reason it is assumed an average value for the viscosity which is the product of the average packing factor in operation conditions and the density of the pebbles.

Pressure in the storage of bulk materials has some differences compared with a fluid in containment. In case of a common fluid, the hydrostatic pressure ensures that at the same height, pressure has a constant value; thus pressure is dependent only on the depth for an incompressible fluid; and taking into account that velocities are very slow dynamic pressure can be neglected. In case of the storage of bulk materials the pressure distributions does not answer to any already known analytic expression and must be estimated with empirical expressions based on the properties of the material, the geometry, and the friction forces created within the fluid and with the walls which origin forces in the opposite direction of the pressure. See figure C.1

But this is not the only reason to explain the big differences and the irregularities of the pressure distribution in a pebble bed. Taking into account how the forces are transferred, we can imagine a very complex situation where the force created by i.e. the mass of pebble, is distributed between its neighbor pebbles, but simultaneously they transfer also the forces. That fact and the inelasticity of the collisions makes it impossible to talk about hydrostatic pressure in case of bulk materials.

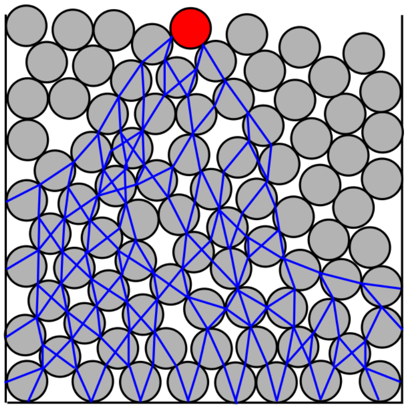

Figure D.3: Stress transmission in a pebble bed [NN 2]

Pressure forces originated by temperature gradients are not taken into account in this study, because in case of operation condition, the changes on temperature are expected to be low. But it is necessary to remark, that the thermal stress studies performed in ANABEK [Babilas 1992], the effect over the pebble bed are stronger stress forces which can be added to those produced by friction.

Viscosity is the main friction mechanism that is found in common fluids but there is not any feasible equivalence with the friction between pebbles than can ensure the same behavior. In case of pebbles, the friction forces are in origin the result of $F_r = \mu_{friction} \cdot N$ meanwhile in fluids is the product of viscosity and shear rate deformation per time unit.

This idea is used by [Scherer 1989] to think about viscosity as *virtual variable* and assumes that it is not possible to find a relation between its value and the frictional parameters of the pebble bed. Following this idea and taking into account studies done in case of Couette flows applied to simulation of granular flows, when shear rate is big enough, it saturates and remains constant [Thompson and Grest 1991] having as a consequence the saturation of the shear stress. In other words, the possible tangential deformation of the fluid is limited to a certain value, which will occur when the walls of the containment are rough enough to ensure that velocity on the wall surface is zero. A maximum value for the shear rate is obtained when there is a pure non-slip wall condition and a minimum value when the boundary condition is free-slip.

Then in the equation of the shear stress at a wall $\tau = \eta * \frac{du}{dy}$; we have to fix the value of the velocity term, and as it is proposed that the viscosity term is a virtual variable, hence is possible to make that the shear stress term has the same value to the friction forces over the core wall, these forces have to be obtained by experimental measurements or can be calculated if the velocity at wall surface is known, which is really difficult to determine. Then, it would be only necessary to calibrate the viscosity depending on the shear rate and we will obtain the same relation between relative velocities inside the pebble fluid and he pebble bed. Then, once the *virtual viscosity* that corresponds to a specific case is known and with the use of shear stress profile expressions given by silo theory, it is feasible to obtain a good approximation to the velocity field found at the core reflector. The last statement requires an expression which can give the value of this virtual viscosity as a function of geometry, operation condition, material properties. Due to the lack of experimental data required. This expression is approximated in the present study.

Despite the fact that bingham and pseudoplastic viscosity models are more similar to a pebble flow, finally and after some trials in section F.2 was found that for high values of viscosity and very low velocities of the flow, the influence of viscosity is very low and it confirms in the results obtained by Scherer.

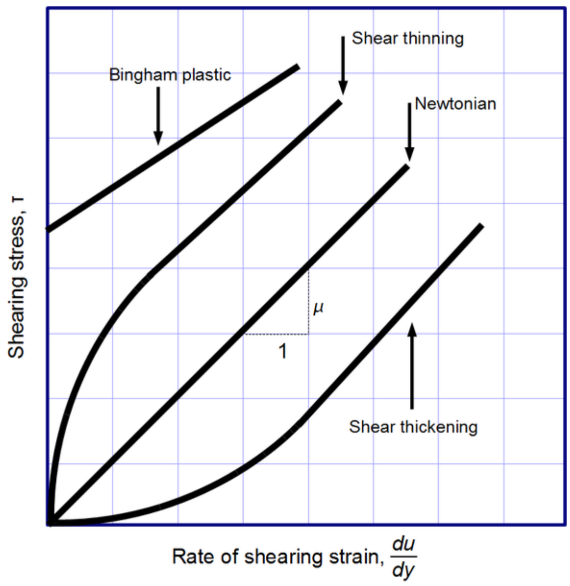

Figure D.4: Viscosity models

D.3.2. Material Properties

The so called *pebble fluid* is the continuum material approach to the flow of pebbles. For this reason it has to be modeled as a liquid in stable thermodynamical state where no heat transfer is allowed because stationary reactor operation in thermodynamical equilibrium is supposed. The density values will be fixed as constant and as it was explained in the previous section, an average value will be taken. The viscosity value have not a major role in the behavior of the pebble fluid behavior when shear stress saturation point is reached, and it is used as a calibration variable to fix the mass flow and thus, the average velocity of the flow.

The characterization tests of nuclear graphite materials [Yu, Lu et al. 2010] showed the high variability of friction coefficient of graphite under different environmental conditions; such as changes in temperature, steam water concentration in the coolant gas or the presence of dust. As long as shear stress depends on friction coefficients and the packing factor, the influence of those factors over the shear stress profile have been plotted using for that porpoise the Janssen's expression C.9.

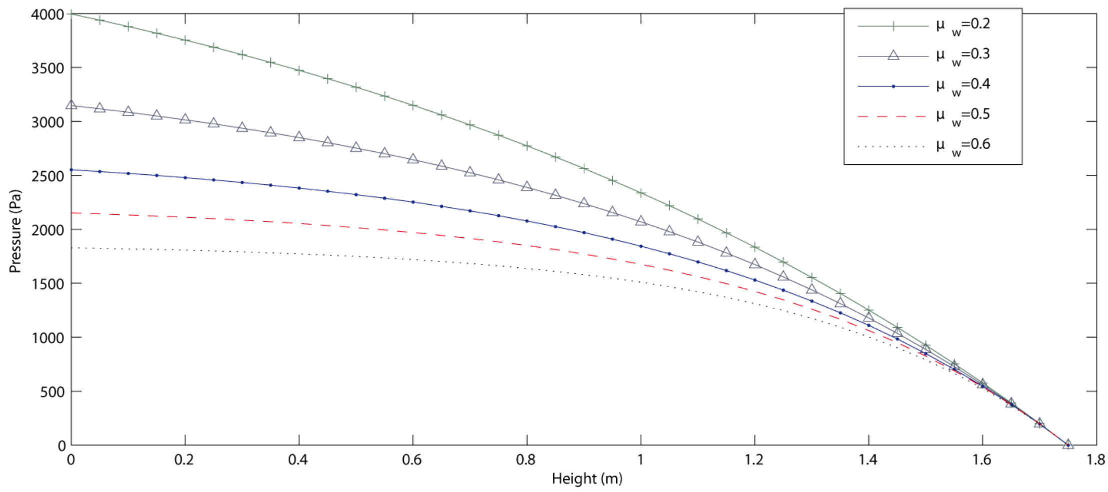

Figure D.5: Pressure at reflector for different values of wall friction coefficient

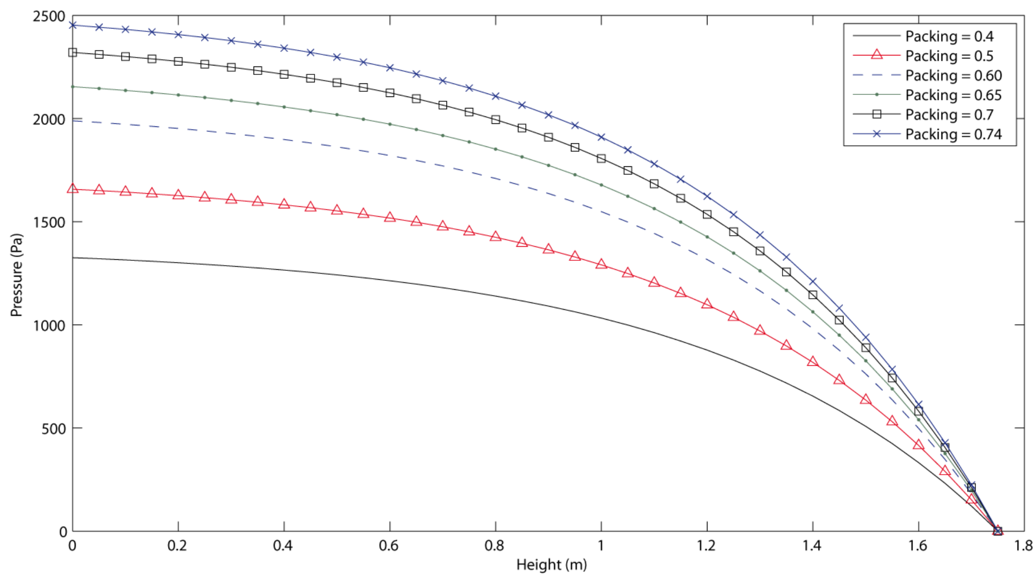

Figure D.6: Pressure at reflector for different packing factor values

In figure D.5 and D.6 can be observed that small changes in friction coefficients or in packing factor values produce not only different values but also a different profile. This variability complicates the modeling of the pebble bed, and require of even more experimental or operational data if high accuracy is required. As a solution, constant average values are assumed in this work , although that could mean loss of precision.

In case of the transport characteristics; heat transmission is not present in the study and then, heat transfer coefficient can be neglected. For the viscosity a Newtonian viscous model will be chosen as it is explained. The value has to be calibrated in order to obtain a similar flow behavior to the one that has been derived from experiments. Reference temperature and pressure can be randomly chosen in case of stationary analysis only, but it is necessary to remind that if different operation points must be studied, the differences in temperature, coolant flow pressure and changes in friction coefficients have to be taken into account.

D.3.3. Geometry and operation characteristics

As operation characteristics can be included all the characteristics that depend directly on the chosen design and all the specific details of every single model.

It is necessary to know the recirculation rate in order to calculate an average velocity, This value can also be derived from the time necessary to recirculate a whole core in the desire operation conditions. The coolant pressure loss is other of the required characteristics needed to configure properly the model.

The geometry by itself can be considered like an operation characteristic because every single design has its own distinctions and they have to be modeled with the maximum precision possible. [Niessen 2009] assets that the simulations done with a geometry should be only compared with the same geometries and same scales in a real design, no scale doctrine is recommended. The geometry is one of the most influencing factors in the flow behavior and for this reason has to be carefully studied. Nevertheless and for reasons of simplification the numerical analysis, small details must be neglected, but always taking into account, that the error made can be large and has to be studied if is negligible or not.

The cylindrical part is in general terms the most simple part of the geometry if the relation H_v/D_v, where H_v is height and D_v the diameter of the vessel, is bigger than 0.8 [Tingate 1974]. This is a reference value and it is explained by the laminar behavior expected. This reason is that in case of a stable laminar regime, the flow needs some distance to develop properly. This relation can be useful in case of a smoother flow desired, but in fact and under the study previously mentioned, factors H_v bigger than the unit do not represent any difference.

The hopper is the final part of the core and it has a great influence over the flow. The explanation to that fact is the change of the fluid particles velocity. In that part, there is a strong change of direction and also, a change of the hopper diameter which cause a great disturbance over the flow. In fact, the results of the simulations done for different boundary conditions show that their influence is smaller than in other parts of the core. In figure F.13 there is an example of the results.

The diameter of pebbles is also an important parameter for the behavior of the pebble bed. A smaller sphere diameter would be desired, but in that case, the permeability of the bed would be smaller, making the heat transfer between pebbles and coolant gas less efficient, which is a non desired consequence.

The main problem when analyzing the geometry is that without an analytical granular flow formulation, is difficult to measure the relative influence of this characteristics.

D.4. Boundary conditions

For the differential problem associated to the continuum framework approach, boundary conditions have to be carefully defined. It is not possible to define them with ideal boundaries only found in theoretical cases. In fact the coupling of variables process directly affect to the type of boundary and the value or expression that represent them. On a first sight, appear different possible solutions, but studies done by [Haff, Hui et al. 1984] explain the feasible boundaries for granular flows approached by viscous fluids. In this study the goal is to set the most accurate boundary condition and to allow the possibility of adaptation for the study in other conditions or geometries.

D.4.1. Inlet/Outlet

These boundary conditions can be chosen in several different ways, but it is important that the streamlines, velocity profiles and the general behavior must be representative of the real pebble bed. In a real pebble bed, the upper part has not any load and it is a simple example of free surface. The pressure of the coolant gas can be set as reference pressure of the fluid. In case of setting a mass flow or velocity condition at inlet and the outlet simultaneously, it is possible to find reverse flow which has no sense; in that case fluid already expelled of the core would get inside again. There are also normal velocity and velocity field boundary conditions, but in the present approach they are the variables that must be predicted.

In the outlet a proper choice of the boundary ensures that flow lines and velocity profiles accurate well to the real pebble bed. The extraction of pebbles is done by means of gravity and simply with a mechanical device with has almost no effect over the previous spheres [Tingate 1974]. It is also necessary to remark that this process is done in discrete times, so it is necessary to fix an average velocity for the continuum approach. But if a normal velocity condition is fixed, the fluid is obligated to leave the outlet with an a flat normal velocity profile, which is not realistic, and could cause problems in the flow lines and the residence time distribution. It is chosen a mass flow condition as the best option. The fluid can flow with freedom. Despite this is the best option, to avoid problems in the flow behavior, the discharge pipe should be modeled longer in the geometries, then the flow can be developed.

D.4.2. Wall boundaries

Walls have the most important role in the definition of the model. The standard options are *free-slip wall* condition, which assumes friction equal to zero over the wall; or *no-slip wall*, which assumes a so rough wall that the velocity over it is zero. It is clear that the real situation is far from the ideal case and actually as it was explained in Paragraph C.4 the pressure induced by the pebbles on the reflector can be defined with precision by the shear stress profile obtained by Janssen's Formula [Janssen 1895] and the actual evolution of that formula performed by [Xiaowei 2010] which is specifically adapted for pebble bed reactors.

But actually, there is no experimental information or any empirical expression which gives the values of the shear stress over the wall. However, if the horizontal pressure is known, the shear stress produced by the pebbles must be a relation between this horizontal pressure and the wall-pebble friction coefficient. For that reason, and taking into account that friction forces are punctual and not surface forces, it is necessary to assume an average shear stress over the wall, which is defined as:

$$P_{friction} = P_h \cdot \mu_{wall} \tag{D.4}$$

Thus, the value of the average friction stress has the same profile than the horizontal pressure and the value as long as it cannot be proved by means of experiments, is not that relevant as the profile. For this reason, in the boundary condition, the horizontal pressured is used instead of the friction stress. As a consequence, is necessary to calibrate the viscosity for the P_h range of values.

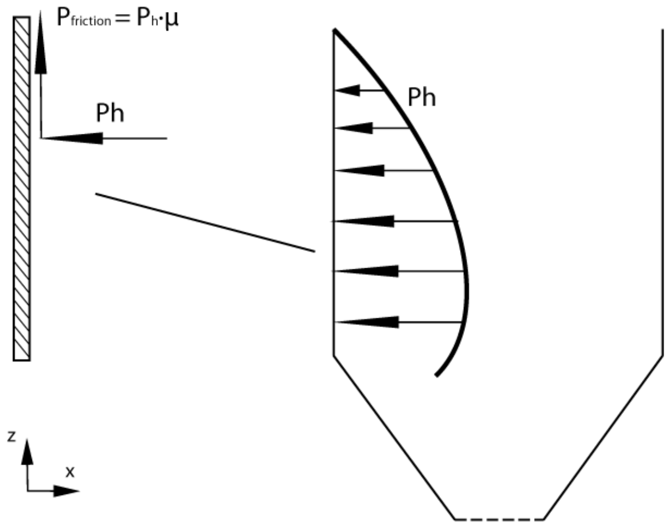

Figure D.7: Force diagram over the core reflector

The expression C.9 depends on the wall-pebble and pebble-pebble friction coefficients, which are not constant but there is not any know expression to express this distribution, and on the core geometry leaving only the height z as variable. This expression has very important consequences because it is the direct relationship between granular and fluid problems. With that boundary, it is possible to represent the friction effects over the core wall with the same values that in the real case. It is necessary to remark that this empirical expression does not allow an accurate shear stress profile and it is probably the largest limitation for the obtaining of more precise results.

Boundary conditions at walls must be specifically determined for each case, because as long as horizontal pressure depends on the core geometry and characteristics there is no general boundary condition. Actually only the core wall boundary should be defined with this pressure profile expression. The hopper cannot be defined by any known and feasible expression. Some studies explain the general behavior [Ravenet 1992] that would be in a coarse approximation a linear or parabolic profile that connects the transition cylinder-hopper pressure with the outlet, where the pressure has to be zero. As a simplification it is fixed a continuum stress profile which would represent the average value.

Another critical region is the transition cylinder-hopper already explained in D.3.3, a rounded transition makes the flow smoother but it is not possible at present to know exactly the values of the shear stress in those locations. In that case it is assumed that flow paths are not affected by friction, therefore a free slip wall condition is chosen, so as for the outlet condition; because in the real core, the expelled pebbles have not effect over the pebbles above.

Appendix E

SOLUTION TO THE FLOW PROBLEM

E.1. Modeling ANABEK experiment

E.1.1. Modeling procedure

The first stage to model a pebble bed core reactor is the construction and meshing of the geometry. However, the more complicated a geometry is, the more CPU time required.

Second step is the definition of the domain, which is given by the operation characteristics: Pressure, temperature, density of the pebble bed and all the general environmental characteristics.

The next step is the definition of the material. Since there is not any viscosity model comparable to a granular flow, it is necessary to assign a value capable to make that the shear stress in the simulation are in the same magnitude order than in experiments. This fact comes from the saturation of the shear rate explained in section D.3.1. To look for the proper viscosity value, a simulation was carried out. In that simulation, a no-slip wall boundary condition was fixed while the rest of the walls where defined with free-slip walls, thus the maximum value of the shear stress over the wall is obtained. Only vertical shear stress is taken into account. The results obtained in the two other directions, are one hundred times smaller, for this reason they are neglected.

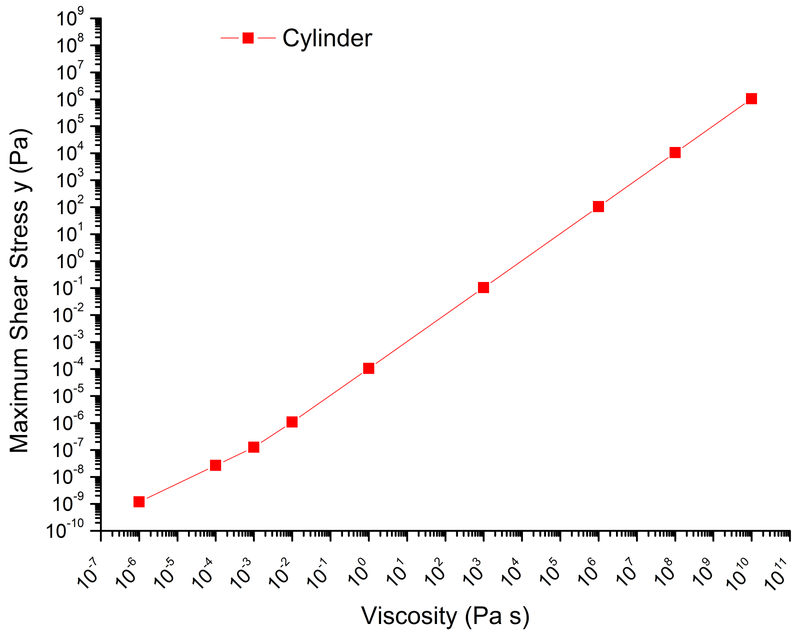

Figure E.1: Maximum shear stress values over the cylindrical reflector core for different viscosity values. No-slip boundary condition fixed

In figure E.1 are the results of the simulation. The vertical shear stress is linear from a viscosity of 1 $Pa\,s$. As a reference, water at 25 $^{\text{o}}$C has a viscosity of $8.9 \cdot 10^{-4}$ $Pa\,s$, and a heavy oil is around $100 - 500\,Pa\,s$. Before that value is reached, from $1 \cdot 10^{-6}$ $Pa\,s$ to 1 $Pa\,s$ a change of the slope can be observed, that means a change on the shear rate. In other words, in that region, fluids with different viscosity values show different velocity profiles. It is necessary to remark, that the values obtained in this test are the maximum possible with that configuration, because a no slip wall boundary condition was chosen.

A value for the viscosity of $1 \cdot 10^{8}\,Pa \cdot s$ is assumed for an initial approximation because the stresses found in the ANABEK experiments are around 10 kPa, the results are resumed in section E.1.1.1.

Finally the expected shear stress profile and its nominal pressure value are implemented in the flow model.

In order to calibrate precisely the model, a simple procedure is followed. First the slope of the simulated residence time distribution curve was fitted to the data. The slope represents the stress profile, and in case of free slip walls, that means no friction with walls, the curve would be almost vertical because if no friction exist, the velocity profile remains flat and all pebbles leave within a very short time difference. On the other side, if no-slip walls are fixed, the residence time curve would have a low inclination, that means a high residence time dispersion. Thus, the model must be between both situations. The next step is to adjust the nominal stress values until both curves fit as accurate as desired.

E.1.1.1. Obtaining a shear stress profile from ANABEK experiments

Obtaining a realistic stress profile is probably the most critical step in all the modeling process. The influence of the shear profile and their nominal values over the flow are very high. However, in the flow and stress experiments of ANABEK pebbles are made of different materials, then there is not any experimental data available about both stresses and flow behavior in same conditions. For those reasons, it is necessary to interpolate a possible stress profile for the pebble flow. The ANABEK stress tests are carried out with ceramic and graphite spheres, while the flow experiment is done with spheres made of polyacetat, whose properties are between graphite and ceramic spheres, closer nevertheless to graphite.

In both figures E.2 and E.3, the horizontal pressure given by silo expression C.9 is plotted for two sets of parameters, cover the complete range of possible values and compared with the results of the ANABEK horizontal pressure simulations.

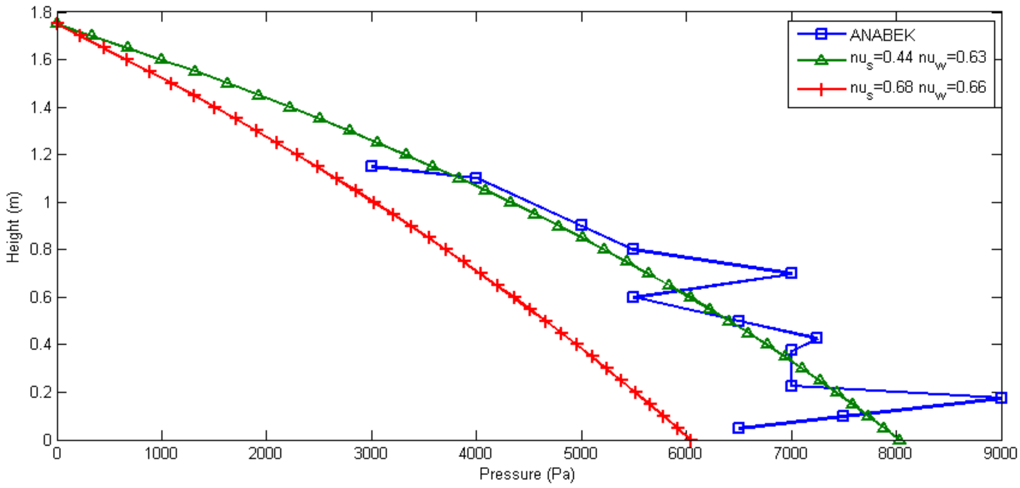

Figure E.2: Horizontal pressures over the core reflector with ceramic spheres in ANABEK compared with Janssen's profiles for different friction coefficients

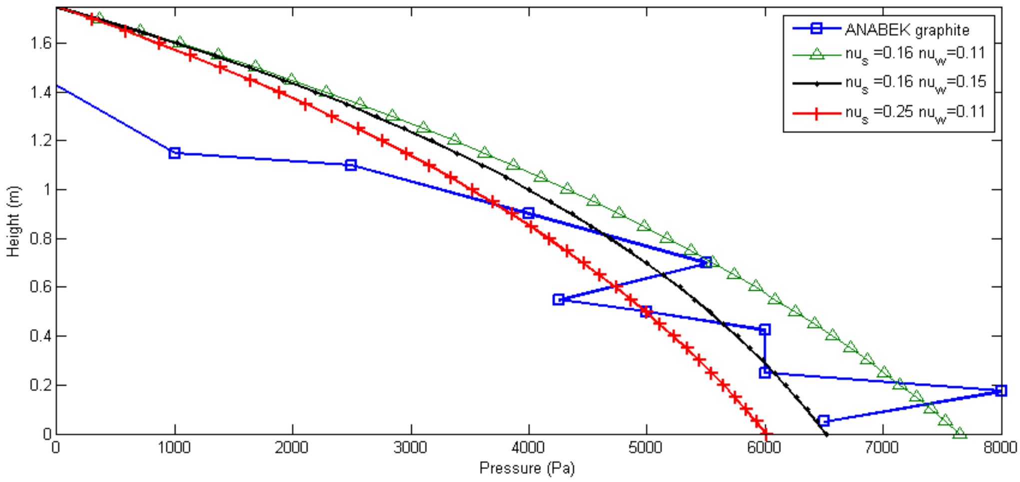

Figure E.3: Horizontal pressures over the core reflector with graphite spheres in ANABEK compared with Janssen's profiles for different friction coefficients

The validity of the shear stress profile expression is very limited by the characteristics of the experiments carried out. The model is 1:6 scaled and the pressure distribution due to height is evidently totally different in the real core.

Figure E.3 show that in case of small graphite spheres the agreement is quite low, but is specially noticeable that there is not any pressure measured at all until 0.5 m below the top surface. It is intuitive to imagine that until a certain height for a light material as graphite, whose density is 1700 kg/m^3, the pressures found are too low to be measured. As a comparison, in the next series of experiments. Spheres are made of a heavy ceramic material, whose density is 2600 kg/m^3, nevertheless the same effect as in graphite test can be observed, the values close to the top surface are smaller than expected.

It is not acceptable to use Janssen's profile in this situation, and for this reason, a similar stress profile is supposed. However, the agreement of the measured experimental values with Janssen's profile is very good and permits thinking about the application to every reactor design.

As long as polyacetat pebbles have closer characteristics to graphite pebbles than to ceramic ones, it is defined a profile called *Step_profile* that has a value of 0 Pa until the height is 1250 mm, similar to the profile in figure E.3. Then, the shear stress grows linearly until a chosen nominal value. The linear profile has been used to simplify the implementation and to test the validity of such a profile.

Several other profiles with different nominal values have been tried. In figure E.4 three examples of applied profiles and their nominal pressure values are shown. Although they do not fit exactly with the stress profiles of figures E.2 and E.3, the approximation is acceptable because first was necessary to measure the real influence of the profile, and then, the goal was to find the profile that makes the flow behave more similar to the one obtained in the flow experiments.

The nominal pressure values, from the stress profiles of the experiments are **referred to horizontal pressure** and **no to shear stress**. As a result, for the chosen value of viscosity $1 \cdot 10^8\, Pa\, s$ is acceptable to fix smaller values than in the experiments. As it is explained, viscosity is a virtual variable which has not any correlation known at present.

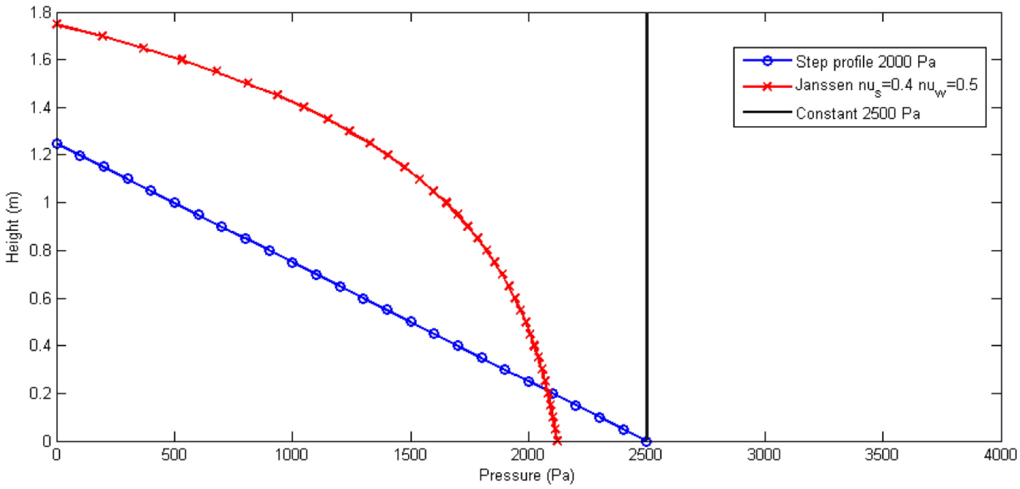

Figure E.4: Different stress profiles tried in the simulations

E.2. Computational solution

The solution of the flow problem, once the theoretical model is clear, will be carried out with the software CFX ANSYS which uses a Finite Element Method (FEM). This software is chosen because it is one of the most extended commercial codes for fluid analysis and has already been validated for many cases.

E.2.1. Particle Tracking as a technical solution

One of the biggest problems found during the development of the present work was the difficulties that involve obtaining information of a single fluid particle or a group of them. In the experiments carried out, THTR-300 and ANABEK test were performed with spherical elements which could be easily identified. But in case of a FEM flow analysis exist two different approaches to solve the problem: Lagrangian and Eulerian approach.

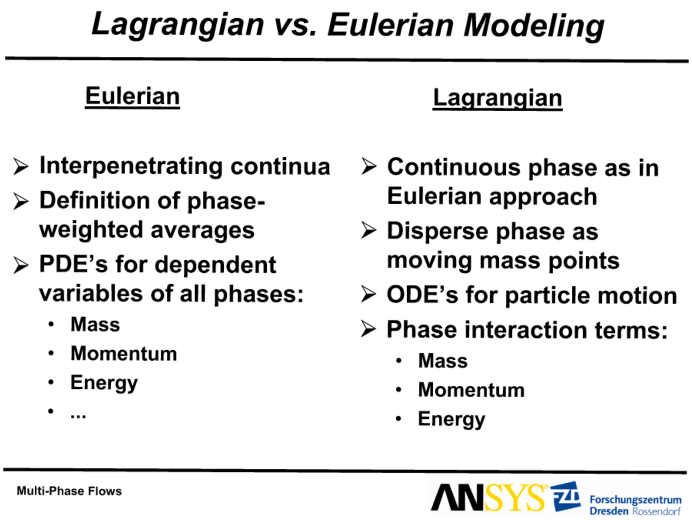

Figure E.5: Lagrangian vs. Eulerian problem flow modeling [Frank 2009]

The Eulerian approach does not distinguish between the fluid particles and makes the analysis in a control volume without taking into account what happens to the particles inside this control volume. Then, it is possible to obtain the flow lines integrating the velocity, but this approach is not capable to calculate what happens to a single particle. For that porpoise is necessary a Lagrangian system, the problem is that this approach requires high computation time and the solving process gets more complicated. CFX ANSYS allows a new method to use a Lagrangian-Eulerian method to simulate the effect of particles in a flow, for example, to study the accumulation of sand inside a pipe, the effect of a two-phase flow with a solid phase, etc. In this work, this method has been used as a part of the fluid defining a two-phase problem where the two phases are exactly the same.

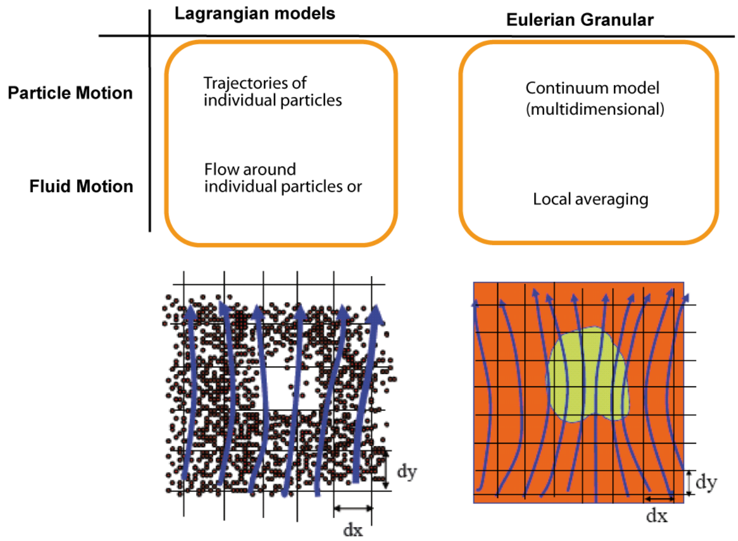

Figure E.6: Comparison between Lagrangian and Eulerian flow models
[Ma and Srinivasa 2008]

The configuration of a two-phase method is challenging for the robustness of the solution and the load of computational work is strongly increased. There is also a problem that comes from the fact of adding a second medium into the main fluid. The interaction between the fluid and the solid particle causes changes in the flow behavior which is not desired at all. For this reason, the tracking particles are configured with one-way equation coupling, in other words, the flow will affect to the solid particle, but not the other way around. Thus, it is possible to work with this virtual particles as an inherent part of the fluid but with the security that they are neutral for the fluid behavior. The tracking particles are defined with the same density and the friction interaction with the Schiller-Naumann model. The interaction between particles are simplified with inelastic collisions, that means a coefficient of restitution e =1.

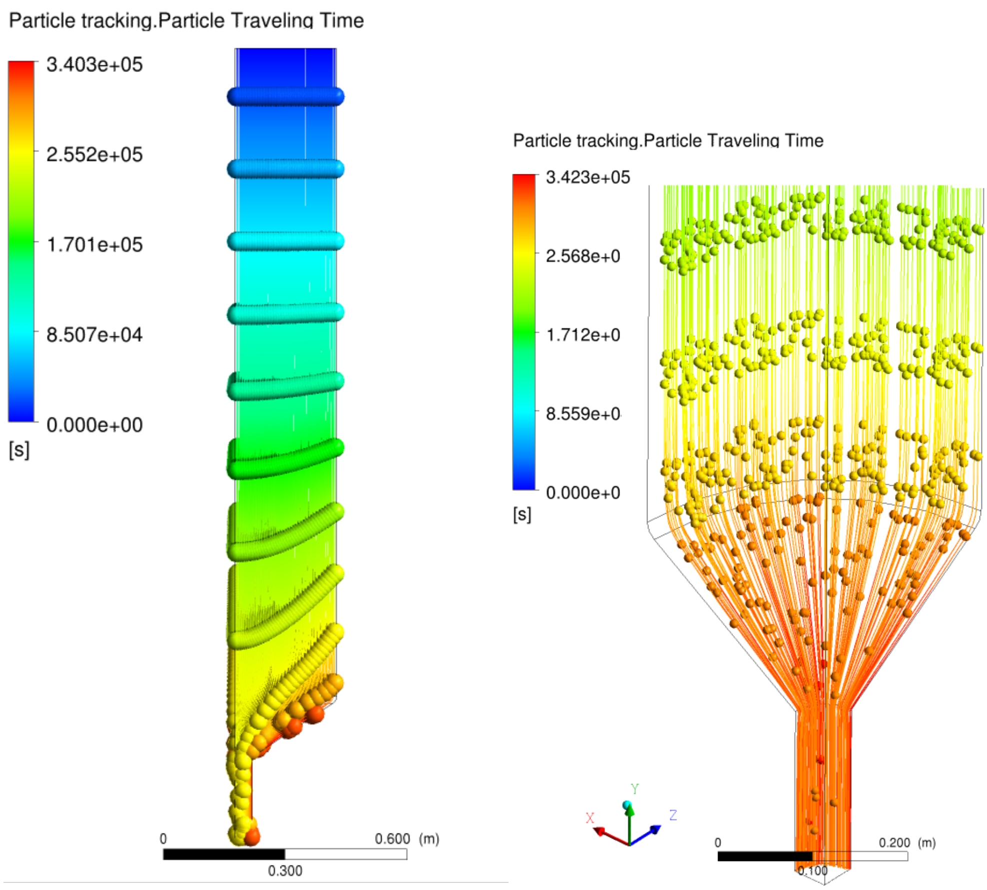

Figure E.7: Visualization of tracking particles for the study of different core regions

This method offers good reliability on the results, but to ensure that the results of the calculations are realistic, it is necessary to implement a code that is used as a pebble chronometer. This code injects a line of marked fluid through the inlet. That means, that from the beginning of the simulation, the first layer of finite elements receives in all of them this marked fluid. The solver does not stop calculating until all the marked fluid particles have left the core.

The use of this technique permits also a better visual comprehension of the grain motion and allows more flexibility in the analysis because the complete history of a single particle is available. To avoid statistical problems, the tracking particles are uniformly injected, controlling the location and their diameter.

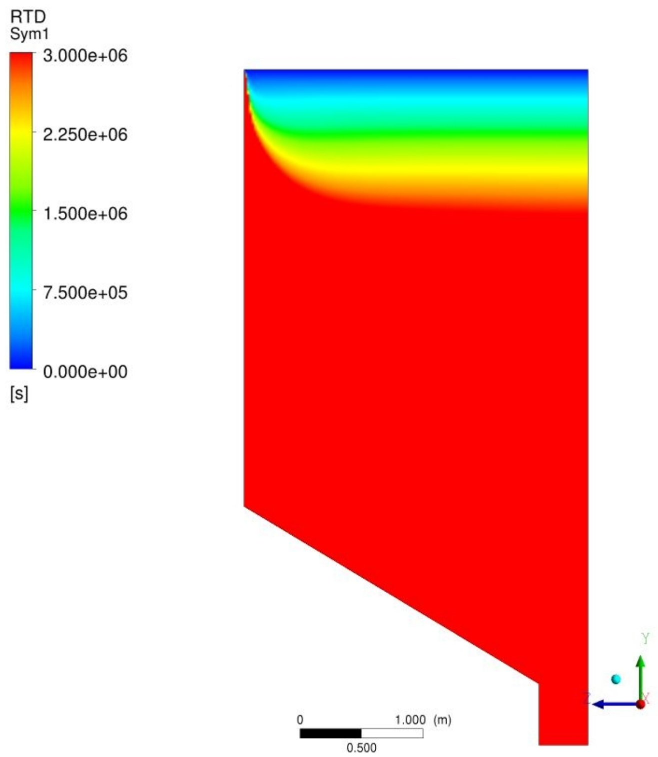

Figure E.8: Time already traveled by the marked fluid while the solver is calculating

E.3. Geometry and material characteristics

E.3.1. Resume of ANABEK flow experiment

In this section a resume of the ANABEK flow experiment [Babilas 1992] is showed.

Geometry:

Model scale	1:6 HTR-Modul 200
Core diameter	500 mm
Core height	1600 mm
Outlet diameter	40 mm
Bottom angle	30º
Refueling rate	4600 pebbles h^{-1}. Equivalent to 1.28% Vol recirculated per hour.

Pebbles:

Material	Polyacetat
Number	360000
Pebble density	$1.41 g/cm^3$
Friction pebble-wall	40 mm
Friction pebble-pebble	0.31-0.4
Refueling rate	0.37-0.51

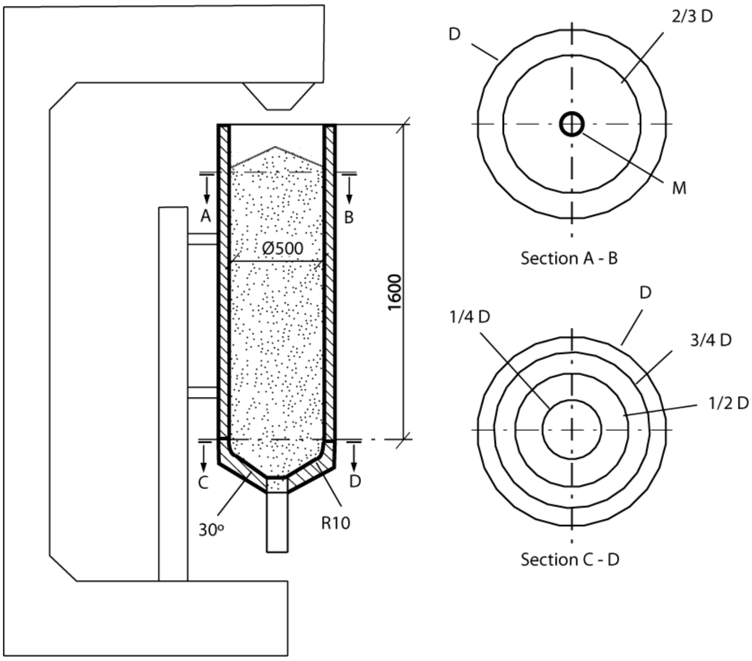

Figure E.9: Geometry of ANABEK model experiment

- Colored marked pebbles
- No cylindrical core, but 24-side polygon
- Cooling system not represented, no injection of cooling gas
- Pebble bed is randomly packed, the it is recirculated to achieve a stable structure.
- Refueling rate is 20 times higher than in real HTR-M 200 core project, no remarkable effects are shown.

E.3.2. Resume of HTR-300

HTR-300 reactor was the pebble bed prototype reactor located in Hamm (Germany). Before its construction a series of experiments called HRB [Bedenig 1966] was carried out to check the flow behavior. The information about that experiment was lost and it is only possible to use the parameters used by [Scherer 1989] in his simulations.

Core diameter	5600 mm
Core height	5800 mm
Outlet diameter	800 mm
H/D:	0.81
Bottom angle	30º
Refueling rate	2.4 pebbles min^{-1}
Number of inlets	8

- Pebbles TRISO pebble fuel
- Fuel pebbles and graphite pebbles mixed

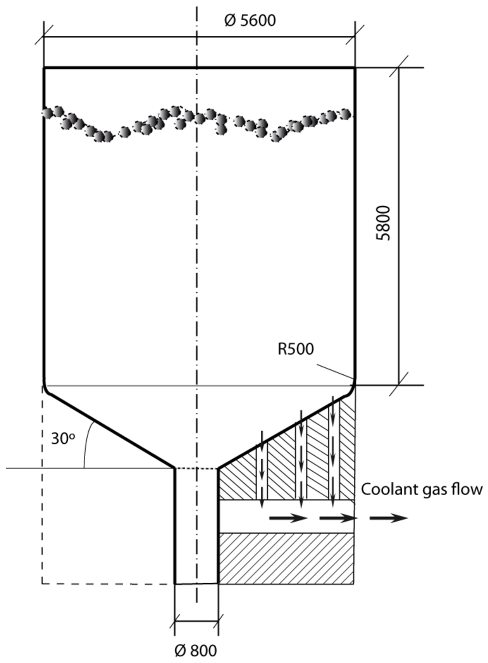

Figure E.10: Geometry of THTR-300 core reactor

E.3.3. Material properties

In the operation of pebble bed core reactor thermal resistant materials are required, the most common material in all the devices inside the reactor vessel is graphite, but the composition and properties of every single component is variable, a research done in China [Yu, Lu et al. 2010] shows the properties for different nuclear graphite composes. Fuel pebbles are the main object of research in this work. The pebbles are known as TRISO, tristructural-isotropic fuel, and consist on a graphite matrix where small Uranium particles are embedded.

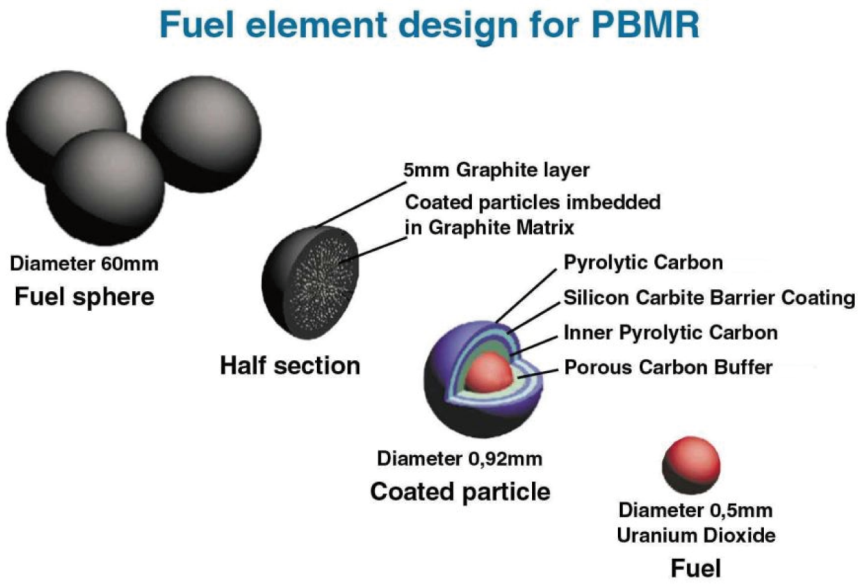

Figure E.11: TRISO fuel pebble [NN 3]

E.4. Miscellaneous

E.4.1. Residence time distribution calculation method

Experiments about pebble flow explained in section C.3 were performed using marked pebbles, also called test pebbles. They were positioned in a thin layer over the core surface, or in defined regions depending on the study goals. Then, they were recirculated and counted as long as they leave the core vessel. When a marked pebble appears must be separately counted. Was developed by [Bedenig 1967] a statistical calculation method called Residence Time Distribution, Verweilspektra-methode in German literature to measure the distribution of the time that pebbles need to travel across the core.

To obtain the distribution, it is defined an interval of p pebbles, then marked pebbles in an interval (ΔTK) are plotted in function of the total number of pebbles that already left in the same interval. In other words, for discrete packs of pebbles, the number of marked pebbles in those packs are counted, and then represented.

It is expressed by the formula:

$$\epsilon(V_{uc}) = \frac{1}{\sum TK} \, lim_{\Delta V_{UC} \to 0} \frac{\Delta TK(V_{uc})}{\Delta V_{uc}} = \frac{1}{\sum TK} \frac{dTK(V_{uc})}{dV_{uc}} \tag{E.1}$$

Where $\sum$TK is the sum of test pebbles, TK means *Testkugel* in German, and dV_{uc} is the differential volume from which the test pebbles are extracted.

In recent studies done by [Niessen 2009] the spectra distribution is summed up and represented in a single curve. This method have some advantages when analyzing the flow of pebbles. The slope of the distribution shows if all the pebbles in the study region leave in a short or large interval of time. This fact indicates the diffusion of the pebbles during the path to the outlet, which is definitely related to the friction forces that are found in that region, thus is more intuitive for the designer to recognize regions or sections in the core where friction forces are bigger. But in the present work in spite of using tracking particles as marked pebbles, there are not any more discrete particles, thus is necessary to adapt the formulation to the solutions obtained with a continuum approach.

First of all it is necessary to change the volume variable to a temporal variable. The time necessary for the circulation of a whole core volume is taken as reference because mass flow and density are constant during operation; therefore the equivalence between Volume and Time is simple. This recirculation time is divided in n periods, and each period is called T_i. ΔT_i is the time passed in the i period. In the present work, it is used a unit, called UVC, defined as the time required for a total recirculation of the core with constant mass flow. UVC means *Umgewälztes Core Volume* in German literature.

Then, the equivalent temporal formulation is:

$$\epsilon(T_i) = \frac{\Delta TK_i}{\sum TK} \frac{1}{\Delta T_i} \tag{E.2}$$

Now it is necessary to normalize the spectra with k factor, hence the time fraction will be equivalent to the volume fraction. So that, for a 10% of recirculated volume leave the same quantity of mass than for 10% of UVC time, and as a consequence can be compared without distinction.

$$k = \frac{1}{\sum \epsilon(T_i)} \tag{E.3}$$

$$\epsilon'(T_i) = \epsilon(T_i) \cdot k \tag{E.4}$$

ϵ' is the normalized percentage of extracted pebbles in the period of time T_i. And taking into account that mass flow and density are constants, volume and time variable are equivalent. Therefore, now is possible to plot which percentage of the test pebbles leave the core in a range of time in terms of recirculated volume, thus 1% of RCV is equivalent to 1% of UVC.

The residence time distribution is a simple but useful tool to study the behavior of the pebble flow. It can be understood not only as a statistical study about how flow the pebbles, but also as a representation of the spheres velocity in the core. In the first section of this chapter is used as a calibration tool following the same idea. In case there were not friction at all in the core, all the pebbles would leave the core almost in the same time which would be represented with a vertical, or almost, curve centered at 100% RCV , while in case of no-slip walls the curve as can be observed in figure E.12 the slope is centered at 500% RCV and the slope has less inclination. In that case, the first pebble leaves the core after the core has been recirculated 3 times, which means that the pebbles at walls flow in relative terms much more slowly than the central ones. Therefore, is also a measurement of the average velocity of the pebbles.

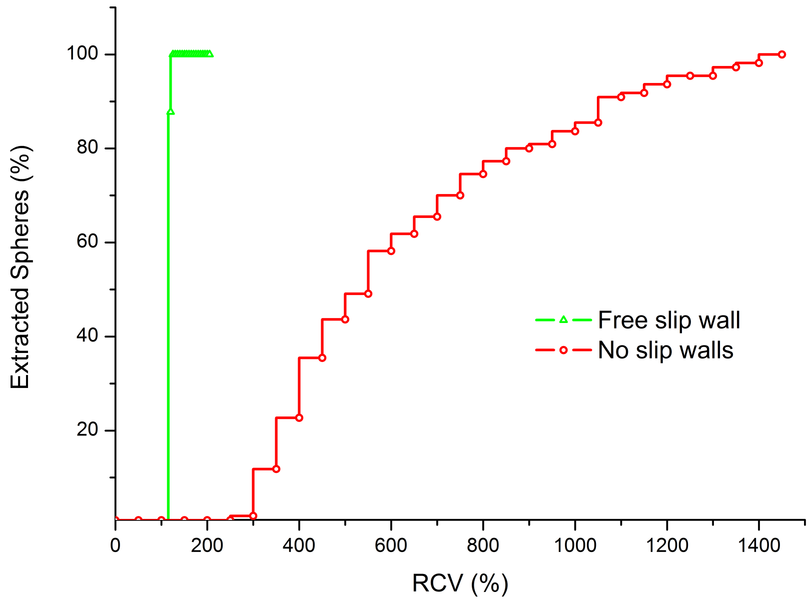

Figure E.12: Residence time distribution for core wall simulations. The slope and the center of the curve are used for calibration of flow model

Appendix F

RESULTS

F.1. Introduction

Multiple assumptions have been made for the development of the flow model , trying in every moment to simplify the problem as much as possible without losing accuracy and physical sense of the real problem. Some of the simplification made are related to parameters or variables which must be analyzed in detail. There is not a clear opinion about saturation of viscosity, the influence of inlet/outlet boundary conditions and the relative weight of the shear stress condition over the flow behavior, and for this reason they are first studied to check if the assumptions made are correct.

The results of the simulations show the influence that coupled variables, material properties, boundary conditions and geometrical characteristics have over the flow model and compare them with the already explained experiments. The non-existence of a single experimental study makes necessary to compare the model with different cases.

F.2. Validity of the assumptions and parameters chosen

F.2.1. Saturation of the viscosity

Changes in viscosity cause no effect in the fluid if the shear rate saturation point is reached. This assumption done in section D.3.1 confirms the experiments of [Thompson and Grest 1991] and allow the definition of a virtual viscosity.

The simulations of the shear rate saturation were carried out with the THTR-300 geometry represented in figure E.10 with a non-slip boundary condition.

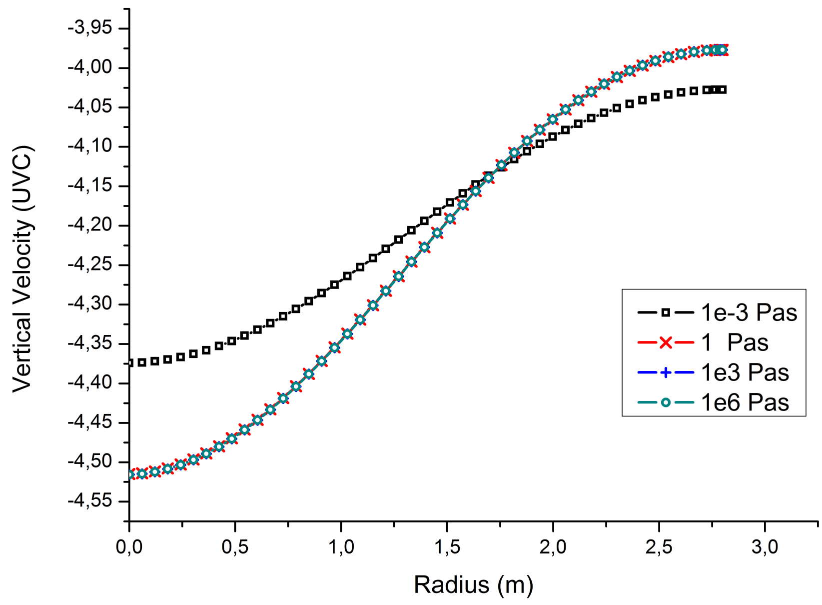

Figure F.1: THTR-300 Vertical velocity profile for different viscosity values at core height 4 m

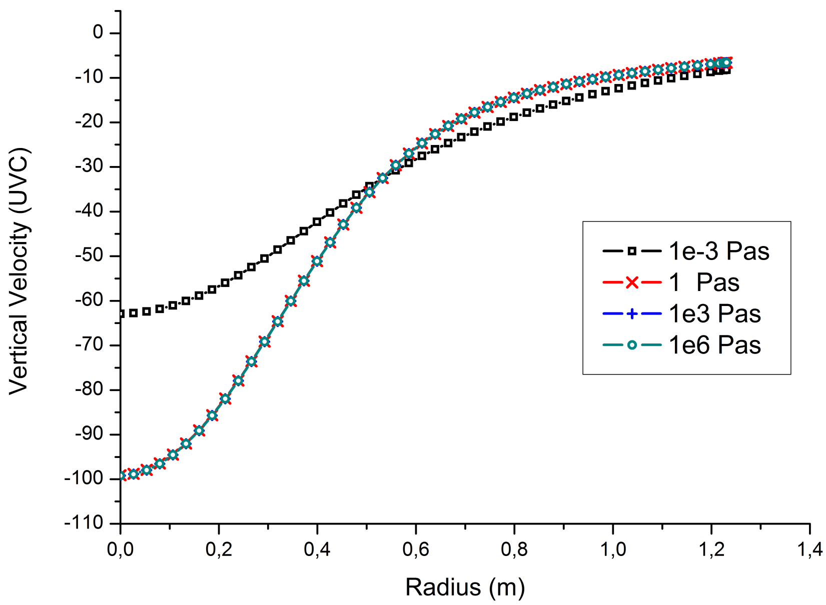

Figure F.2: THTR-300 Vertical velocity profile for different viscosity values at core height 0.5 m

The confirmation of the previous statements is shown in figures F.1 and F.2. Vertical velocity profiles are overlapped for values of viscosity higher than 1 Pa s. It means that a maximum shear rate value is reached. Thus, when viscosity is increased, the velocity profile is not affected but the forces over the wall increase linearly as it is explained in figure E.1.

As a consequence, from 0 Pa to the maximum shear stress value, all values must be positive, exist an intermediate value of the shear stress that makes that the value of shear stress fits with the same value in the real pebble flow. In other words, There is a value of the stresses over the core reflector that makes the pebble fluid behave exactly the same than the pebble bed for every location.

The choice of the virtual viscosity to carry out the ANABEK flow simulations is done according to a simple criteria: experimental data must be implemented in the model avoiding transformation of the real value. In the present work the chosen viscosity, is that, in which a similar shear stress level to the experimental data can be found. A first approach is done for $1 \cdot 10^8$ Pa s and it corresponds to a maximum shear stress of 10 kPa as show the simulation results in figure E.1

F.2.2. Validity of the boundaries

F.2.2.1. Inlet/Outlet boundary condition

The definition of the boundary conditions is not a trivial decision in the solution of the differential problem. In figure F.3 the results for simulations with two different inlet conditions are displayed. The streamlines obtained from a mass flow boundary condition in the inlet are deformed in comparison with the other two which have only a reference pressure condition. This is caused because the flow assumes implicitly an homogeneous normal velocity, which actually is not realistic. In that case, there is a change of the flow direction. The other two streamlines show good agreement with the situation inside the real pebble bed. Two very different viscosities are chosen for that simulations, but as expected, the differences are small compared with other variables like geometry. The assumption of a relative pressure condition at the inlet and a constant mass flow condition at the outlet are the chosen option.

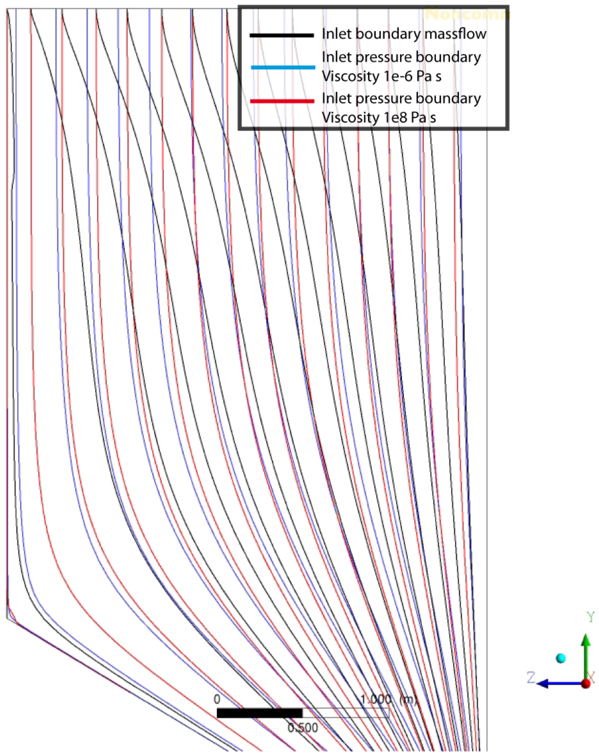

Figure F.3: Streamlines for different Inlet boundary conditions

F.2.2.2. Wall boundary condition

Wall boundary conditions play the most important role in the solution of the flow problem. The standard conditions which are no-slip wall, zero velocity over the wall, or free-slip wall, no friction over the wall, are not realistic and either could not be used in a coarse approximation. A third option is chosen to prove the assumptions done about the effect of friction forces over the flow. The chosen boundary consists on a direct definition of the shear stress over the wall, this profile should be obtained from experimental data or an empirical expression.

To check the real influence over the flow of that boundary conditions, simulations with different shear stress profiles are carried out. The reason to use those profiles can be found in section E.1.1.1 and a graphic description of the profiles can be found in figure E.4

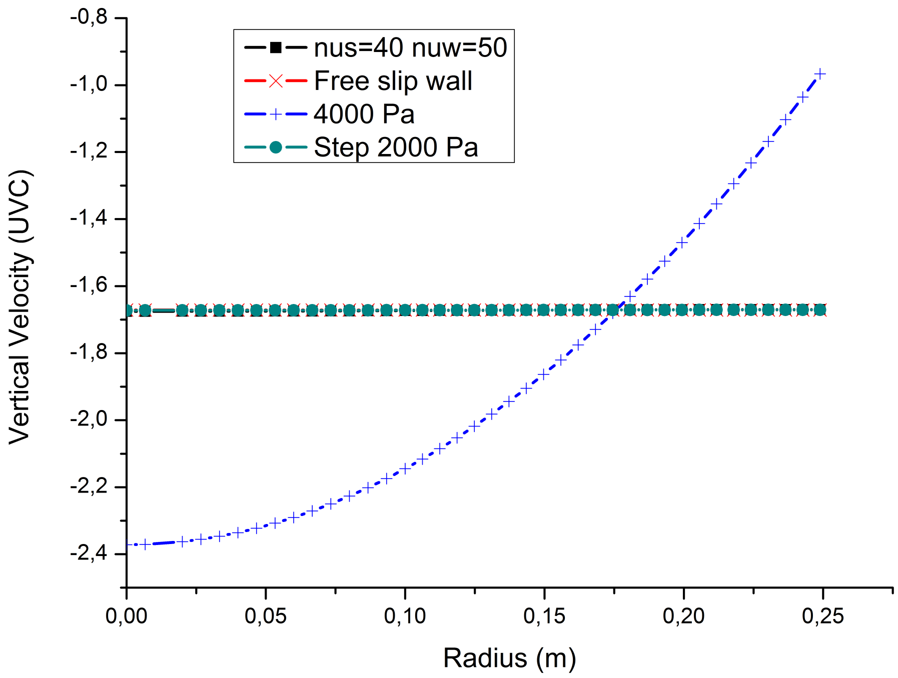

Figure F.4: Vertical velocity for different shear stress profiles at core height 150 cm

In the upper part of the core, the effect that shear stress has over the flow can be observed. In the three overlapped curves in figure F.4 the shear stress value is 0 Pa. Meanwhile the profile defined by a constant value of 4000 Pa shows an already developed velocity profile.

In the middle core region the different velocity profiles are caused by the development of the flow under different shear stress patterns. No friction at walls, like with free-slip boundary, causes a completely flat velocity profile, meanwhile higher pressures cause more developed profiles.

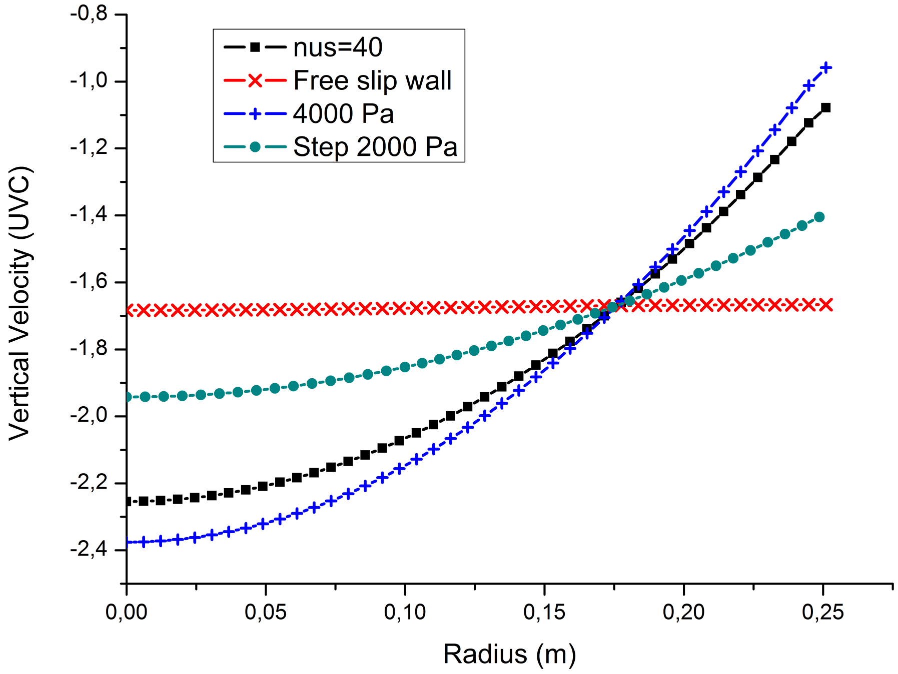

Figure F.5: Vertical velocity for different shear stress profiles at height 50 cm

However, those effects are reduced at transition core-hopper zone. In figure F.6 the velocity profiles are very similar independently of the shear stress value. Nevertheless, in the hopper the friction forces are supposed to be lower than in the cylindrical part [Ravenet 1992], but despite that fact, this similar behavior must be produced by the geometry effects of the core. It seems clear that hopper geometry has great importance and confirms the experiments done about the influence of core geometry [Tingate 1974].

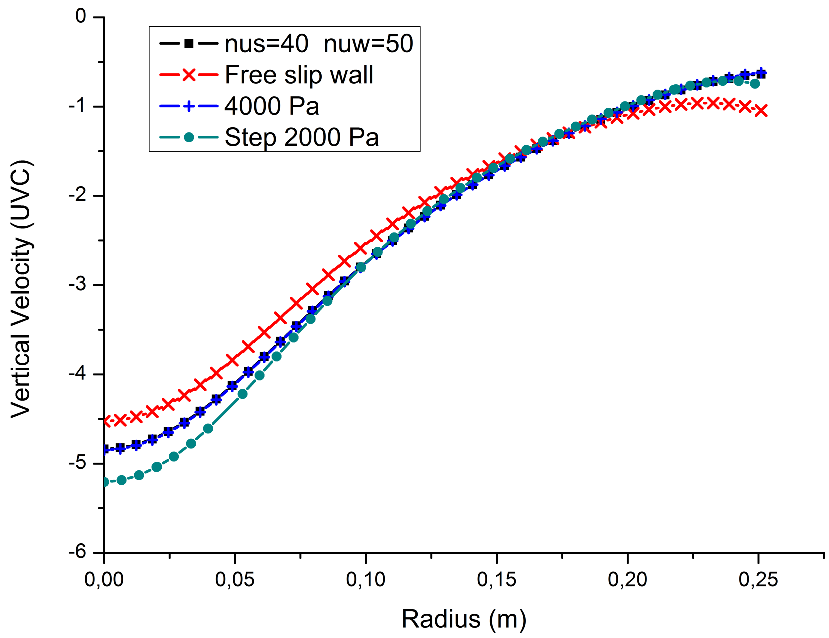

Figure F.6: Vertical velocity for different shear stress profiles at height 15 cm

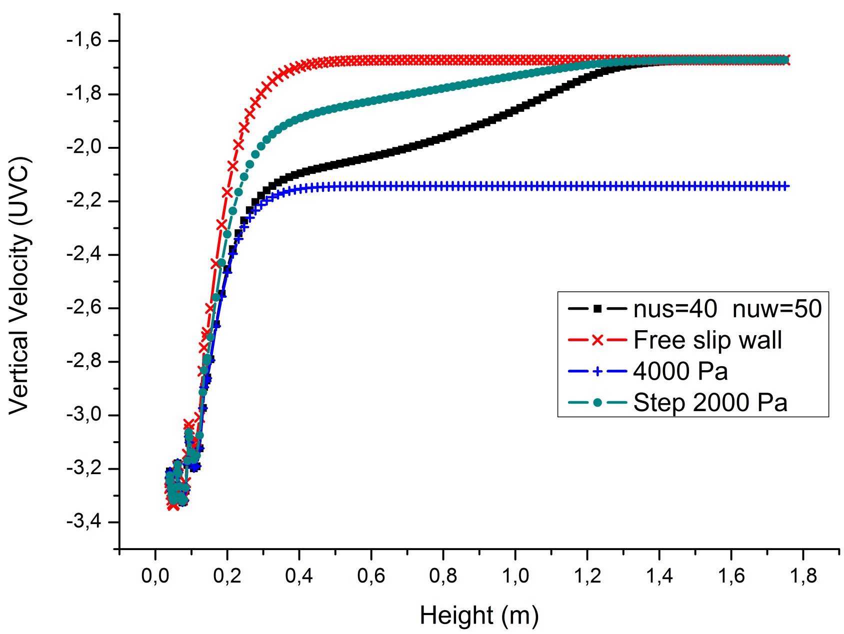

Figure F.7: Vertical velocity for different shear stress profiles at Radius 10 cm

In both figures F.7 and F.8 can be better appreciated the influence of the shear stress profile and the hopper geometry effects. Free-slip and 4000 Pa stress profiles are both constant and origin also very regular velocity profiles. Meanwhile variable stress profiles create variable velocity profiles. This fact confirms the supposition that it is possible to model every shear rate with the proper value of shear stress. As a second consequence, the influence of the hopper is again very clear. When the pebbles arrive at the transition region cylinder-hopper, the velocity field converges to the same values.

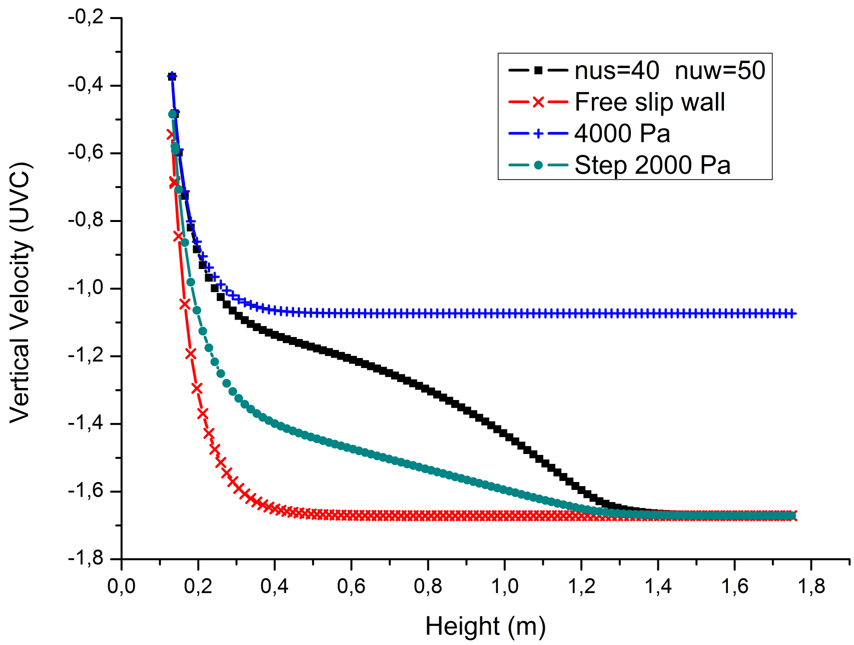

Figure F.8: Vertical velocity for different shear stress profiles at Radius 24cm

Velocity profiles in figures F.7 and F.8 show big differences. In the upper part of the core, the velocities are almost the same, or very similar in case of shear stress profiles whose values are low in that part. The 4000 Pa profile shows clearly the difference between the influence of friction forces at wall. However, in the case that velocity is measured close to the core center, R=10 cm, the velocity increases when the flow arrives to the transition region, but in the simulations done close to the side reflector, the velocity decrease quickly.

After the simulation results, it can be concluded that wall boundary condition have the largest influence over the flow behavior. This fact is helpful because reduces the number of variables that have to be coupled, but also requires of accuracy experimental data in order to obtain a robust solution.

F.3. Results of the flow simulations

The flow behavior model must be able to predict the evolution of the streamlines, the residence time distribution and the velocity profiles.

F.3.1. Streamlines and flow characteristics

In case of streamlines, the only valuable experimental data found comes from the experiments done by Bedenig and their visual results [Bedenig 1966]. The boundary conditions chose after the initial simulations done are a relative pressure condition at the inlet and a mass flow condition at the outlet. The other possible conditions and the reason the reject them are in section D.4.1. The material is defined with two different values of the viscosity to check the real influence of that value over the flow.

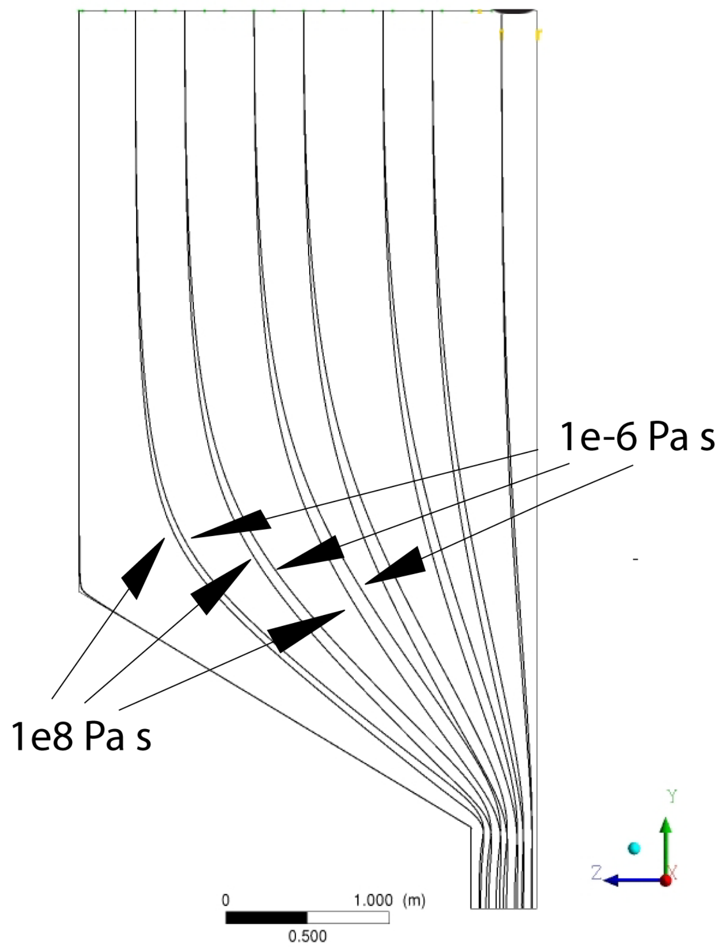

Figure F.9: Streamlines comparison for different material viscosities.
Relative pressure boundary condition at inlet

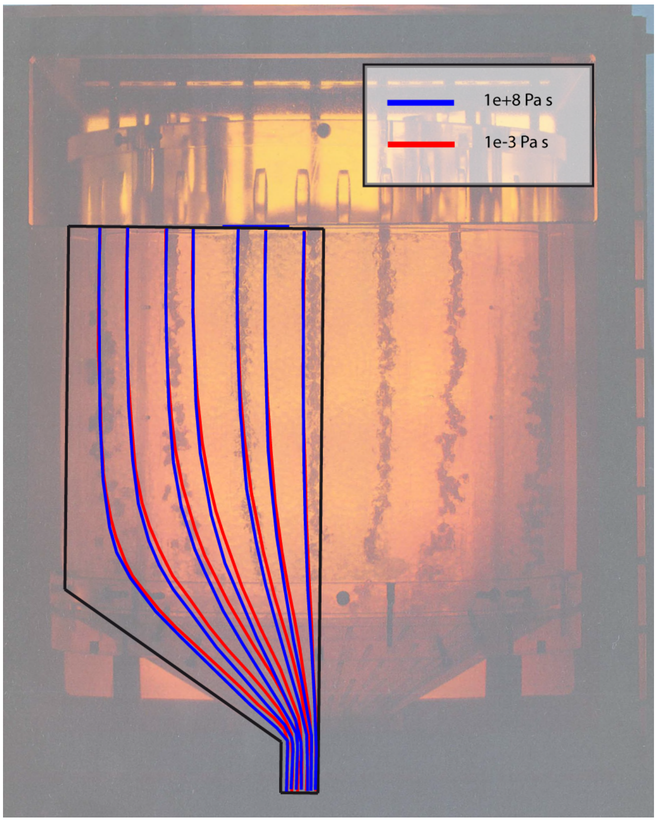

Figure F.10: Comparison between THTR-300 model experiment and simulation results for different viscosities [Bedenig 1966]

In figure F.10 the streamlines obtained from the simulation in figure F.9 are compared directly with the results of the visual experiments performed for the THTR-300 design in the 1:6 model. The agreement with the experimental results is good. The trajectory of the streamlines obtained in the simulation fit properly with the flow of colored pebbles in the experiments. The experimental procedure carried out is explained in section C.3.3.

Finally the contour-plot of the vertical velocity is also shown in figure F.11. The zones close to the wall and specially in the transition cylinder-hopper have very low velocities, which can cause the stagnant of the flow. Despite that fact, the velocity never decreases to zero but it is necessary to analyze carefully that region of the core in order to optimize the geometry.

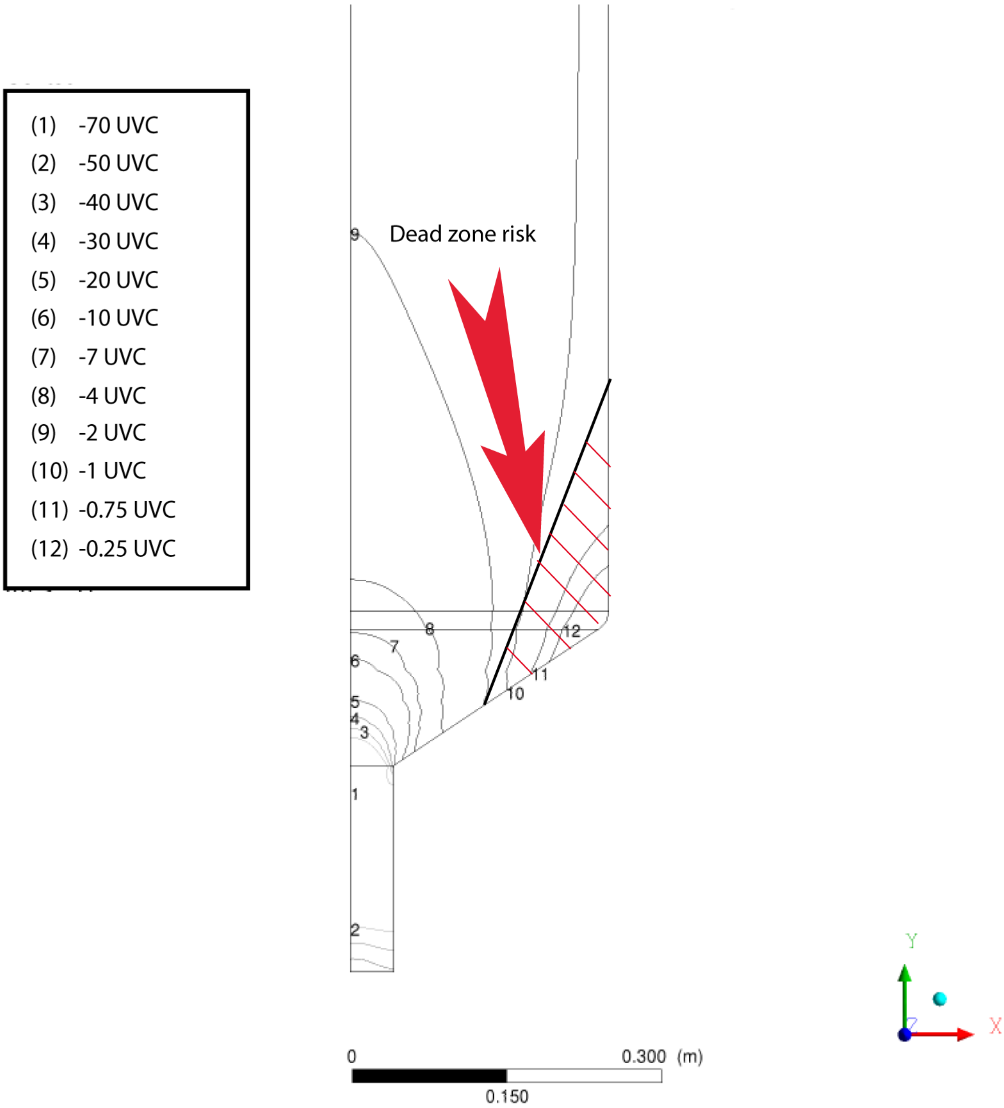

Figure F.11: Vertical velocity contour-plot. Danger of stagnant flow in low velocity regions

F.3.2. Residence time distribution

Residence time distribution, from now RTD, is the chosen method to study the flow behavior and the velocity fields, it is explained in section E.4.1. The validity of the present model requires that results obtained in the simulation are comparable to the data derived form ANABEK flow experiments [Babilas 1992] which are explained in detail in section C.3.4 . The results are also compared with the the simulations performed with a D.E.M. method [Niessen 2009].

The simulations have been performed for the hopper and the whole core. A geometry and a mesh was built for each one of the parts because it was not possible the injection of tracking particles apart from the inlet. The hopper is individually studied because its influence over the flow requires a careful verification. Then, the whole core is studied for different radial positions.

The goal is to test the influence of the different core regions over the flow, but specially the wall effects over the whole flow. The tracking particle injection positions are represented in figure F.12.

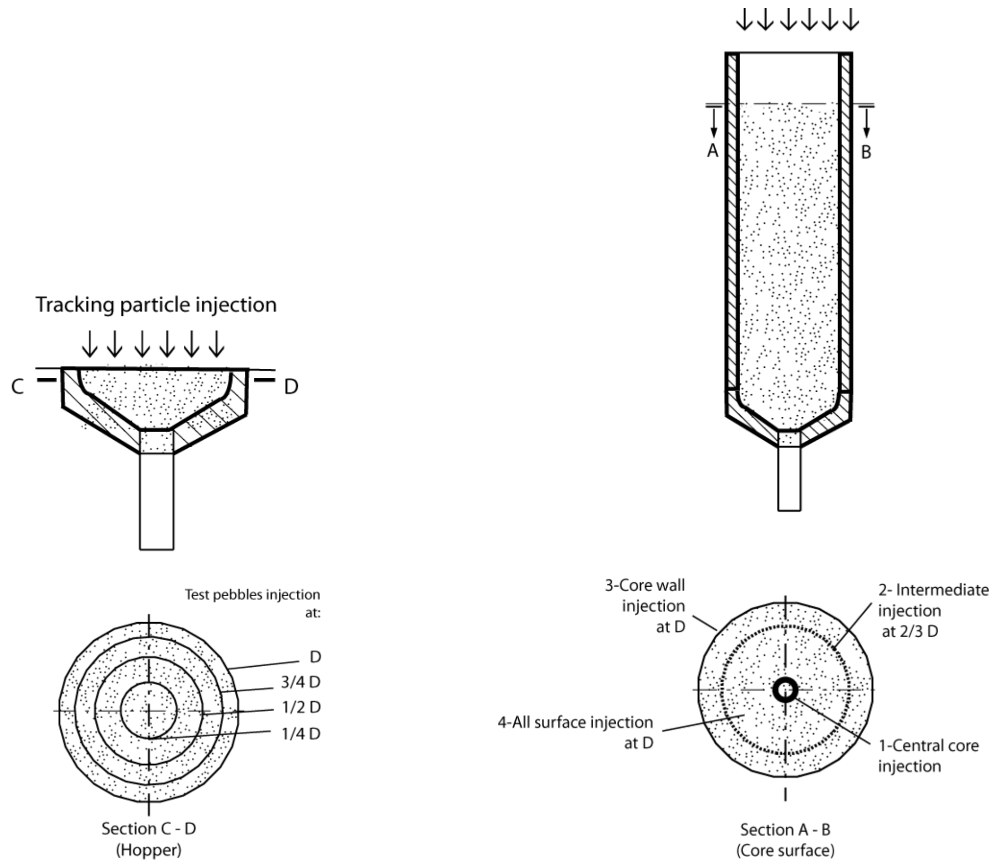

Figure F.12: Injection of tracking particles in ANABEK core model

F.3.2.1. ANABEK simulations at hopper

The simulation of the hopper is carried out injecting a layer of pebbles over the whole surface of the hopper geometry model showed in figure F.12. Meanwhile in the ANABEK experiment, the marked pebbles were located on rings. This difference in the simulation method could derive in statistical error due to the differences in the number of particles analyzed for each region.

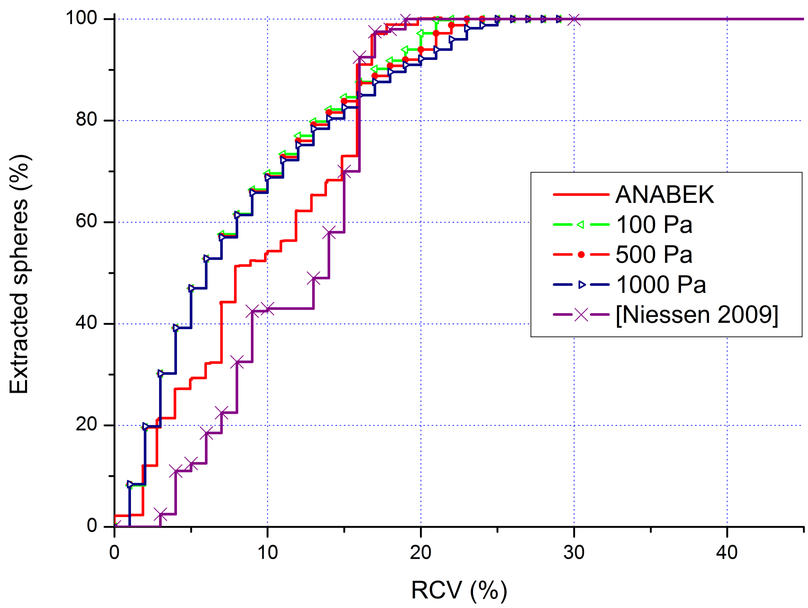

Figure F.13: RTD in the hopper for different wall shear stress profiles in the boundary conditions

The results obtained in the hopper, figure F.13, show an intermediate level of agreement. The most interesting fact is that all the RTD from the simulations follow the same pattern until the 80% of the spheres have already been extracted. Then, they separate depending on the fixed shear stress. Friction forces in that region as previously said, are lower than geometrical influence, or at least comparable, otherwise the difference should be significantly bigger. The change of the flow direction was assessed as the probable geometrical cause for that difference.

The results obtained by Niessen do not match with higher precision. However, they predict better the tendency of the curve. In that region, is probable that differences between discrete and continuum approach are big from a theoretical point of view, because the discrete method can study the interactions with the wall and other pebbles for each pebble separately, but in case of continuum framework there is an average calculation of the interactions with a loss of accuracy.

In all cases, linear shear stress profiles are chosen. Nominal pressure value at hopper beginning is 500 Pa and decrease linear until 0 Pa in the outlet. This profile is a coarse approximation to the expected values at hopper. This approximation is acceptable compared to the results of ANABEK stress profile patterns in section E.1.1.

F.3.2.2. RTD at core wall

At core wall, friction between pebbles and side reflector govern the pebble behavior. Figure F.14 shows the effects over the flow for different shear profiles. The use of different profiles was essential to understand the relative weight of this section compared to the rest of the core. Despite the fact that stress profiles have similar nominal pressure values, the flow has a completely different behavior, therefore an accurate description of the friction forces at the side reflector is absolutely necessary. This variable in relative terms, has the highest influence over the flow.

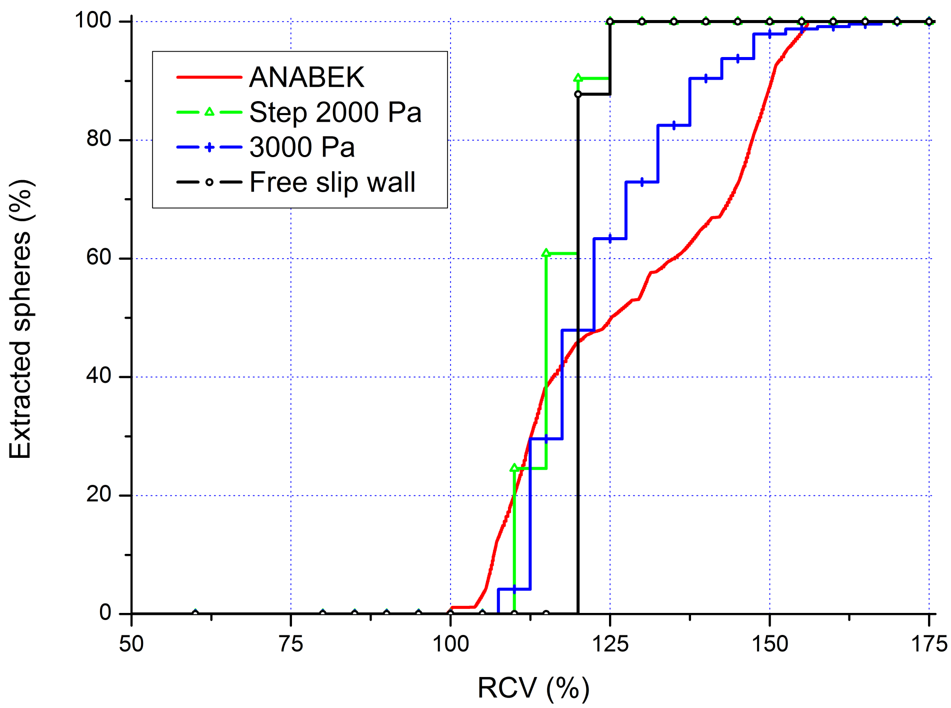

Figure F.14: RTD for different shear stress profiles

For that simulation a 3 cm ring of pebbles in the outer ring is located on the top of the whole core. In case of the experimental procedure, it is supposed that pebbles are in contact with the core reflector but there is not more information available. See locations in figure F.12.

The simulation results do not match well with the results of the experiments. This fact was a source of problems because in case of choosing a more similar profile, for example in figure F.14 4000 Pa stress profile fits better, the results obtained in the other regions of the core did not match, in figure F.21 it is shown. That fact is explained by the different effect of long range forces in continuum and granular flows as it was explained in section D.2. Therefore, long range forces produced by the transmission of energy between pebbles have to been taken into account. Their effect reach about 5 pebble diameters.

F.3.2.3. RTD at top pebble bed surface

A whole layer of tracking particles is placed over the core surface and recirculated trough the core, see figure F.12. In the first simulation carried out, several profiles were tested in order to check which accurate better to the flow results of ANABEK. In the second series of experiments different nominal pressure values are tried.

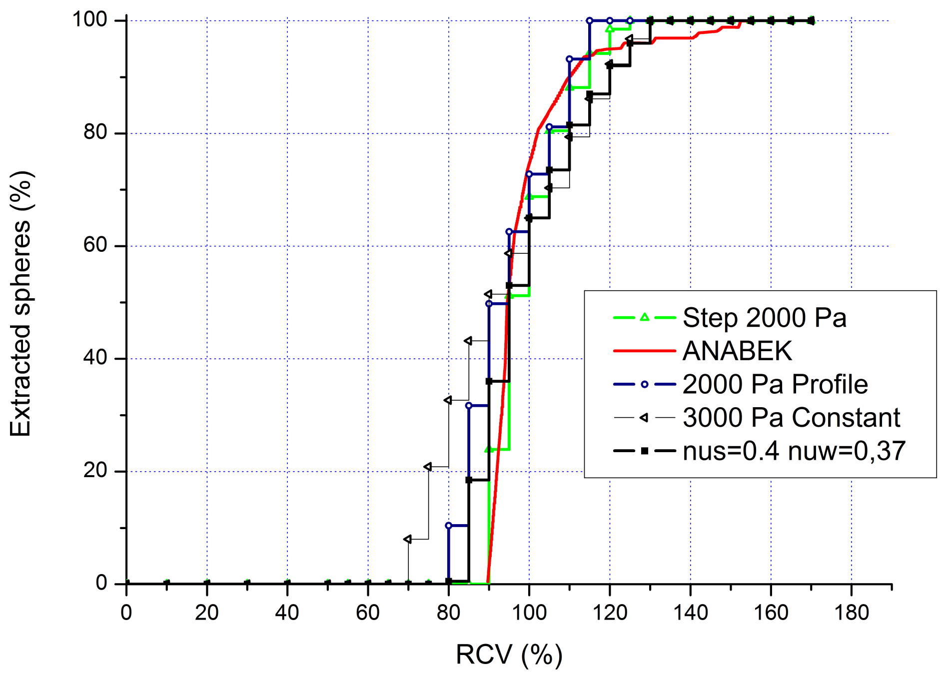

Figure F.15: RTD for different shear stress profiles. Injection of a tracking particle layer over the core surface

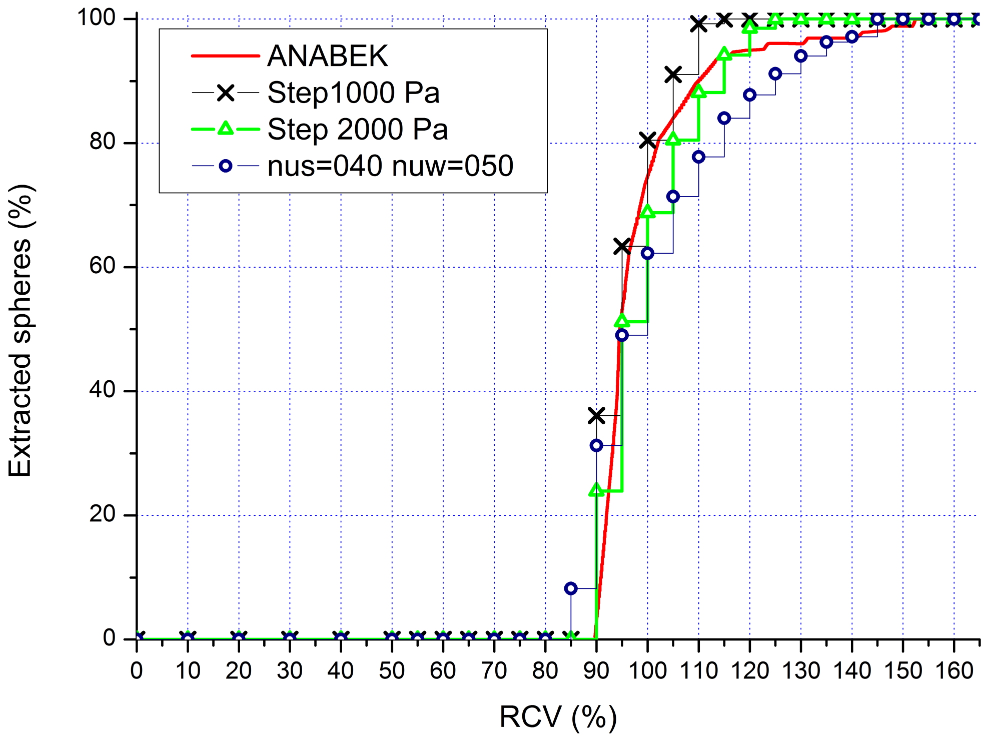

Figure F.16: RTD for different shear stress values. Two different profiles are tested

Figure F.15 shows that the best choice for the shear stress profile is the so called *step profile*, see figure E.4. This conclusion matches with the assumptions taken previously in section E.1.1.1. The slope of the RTD curve is related to which kind of profile is defined. Meanwhile the nominal value of the profile must be chosen depending on the curve spread which is represented in figure F.16.

F.4. Validation of the results

The best configuration for the ANABEK flow experiments corresponds to the results obtained with a *Step profile* of 2000 Pa as nominal value for the cylindrical part. A linear profile in the hopper that starts at 500 Pa and decreases to 0 Pa in the outlet. The curved transition region between cylinder and hopper is defined with a free-slip wall as a simplification, that means no friction at. In the outlet also a free-slip wall condition is set. The discontinuity of the shear stress was assumed because the shear stress is unknown and the region is small compared with the rest of geometry. See figure F.17.

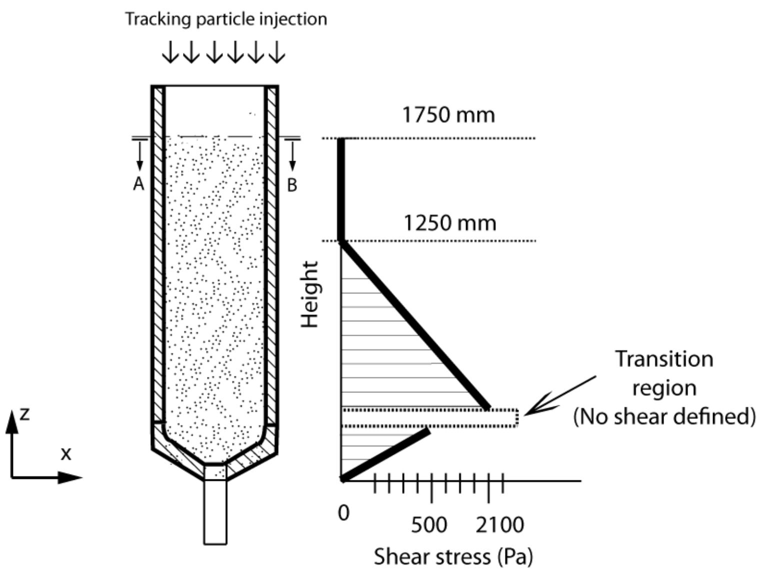

Figure F.17: Scheme with the shear stress profiles. Step profile at cylindrical part and hopper 500 Pa linear profile

F.4.1. Residence Time Distribution

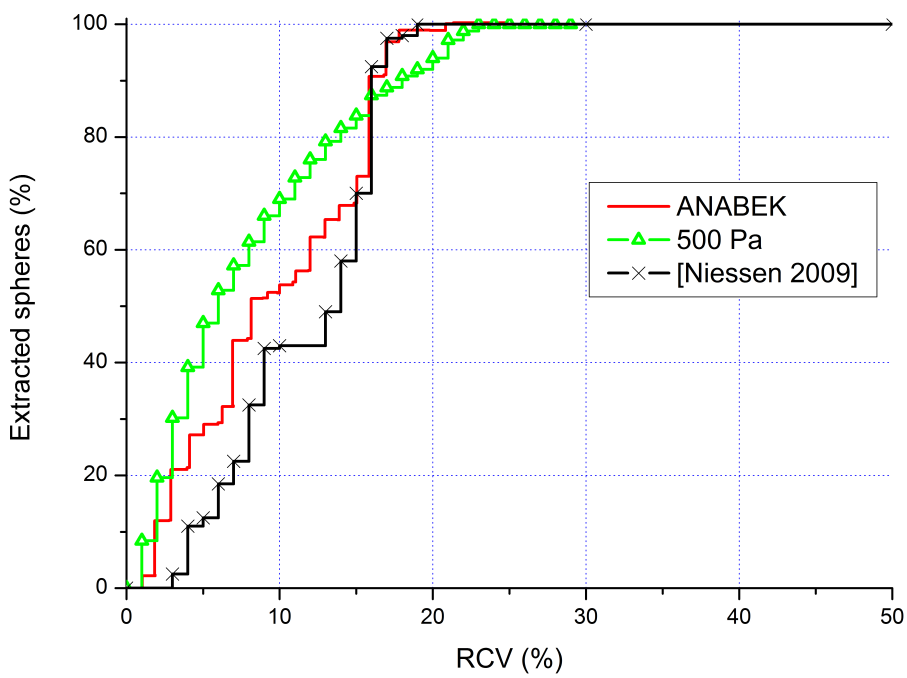

Figure F.18: RTD at hopper. Comparison of the study case with D.E.M. simulations and ANABEK

In the hopper, figure F.18, the results obtained, show that the model is able to predict the tendency of the RTD curve from ANABEK tests, nevertheless, the results obtained by a D.E.M. method suggest that in this region are involved more variables or factors which actually are not known, because that method is neither capable to predict with precision the values of the curve.

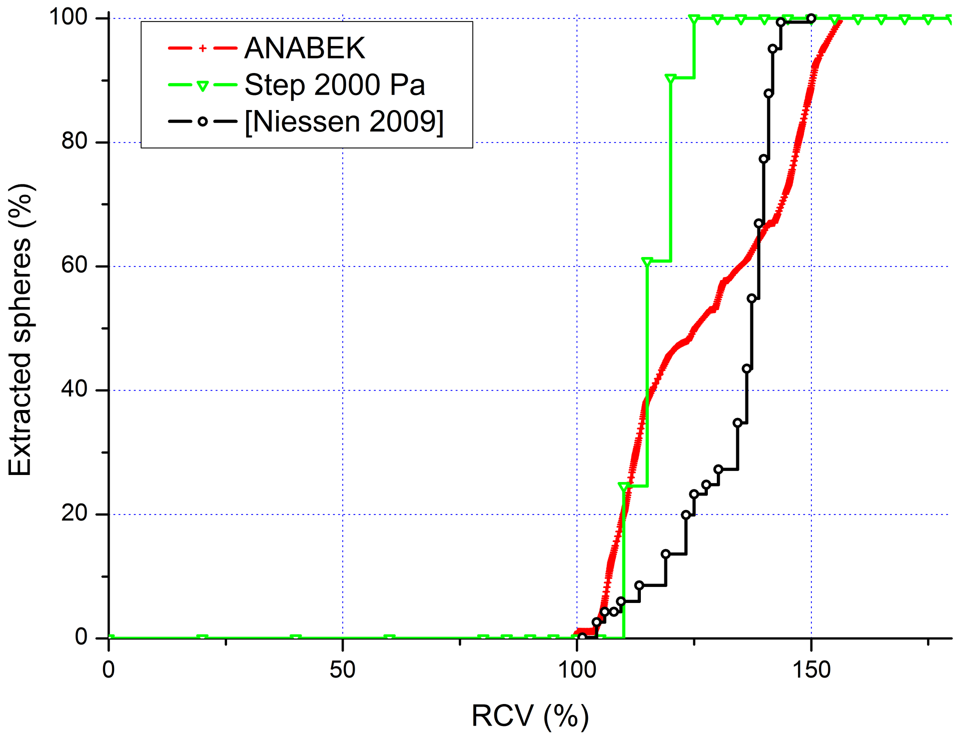

Figure F.19: RTD at core wall. Comparison of the study case with D.E.M. simulations and ANABEK

The simulation results at core wall are only able to predict the beginning of the first leaving pebbles, figure F.19. The simulations carried out by Niessen, are also quite different to the results of the experiments. This region of the geometry is the most difficult to be modeled and the reason can be found in the fact that friction forces are very irregular in that region, and also, statistical issues should be taken into account for a proper data analysis.

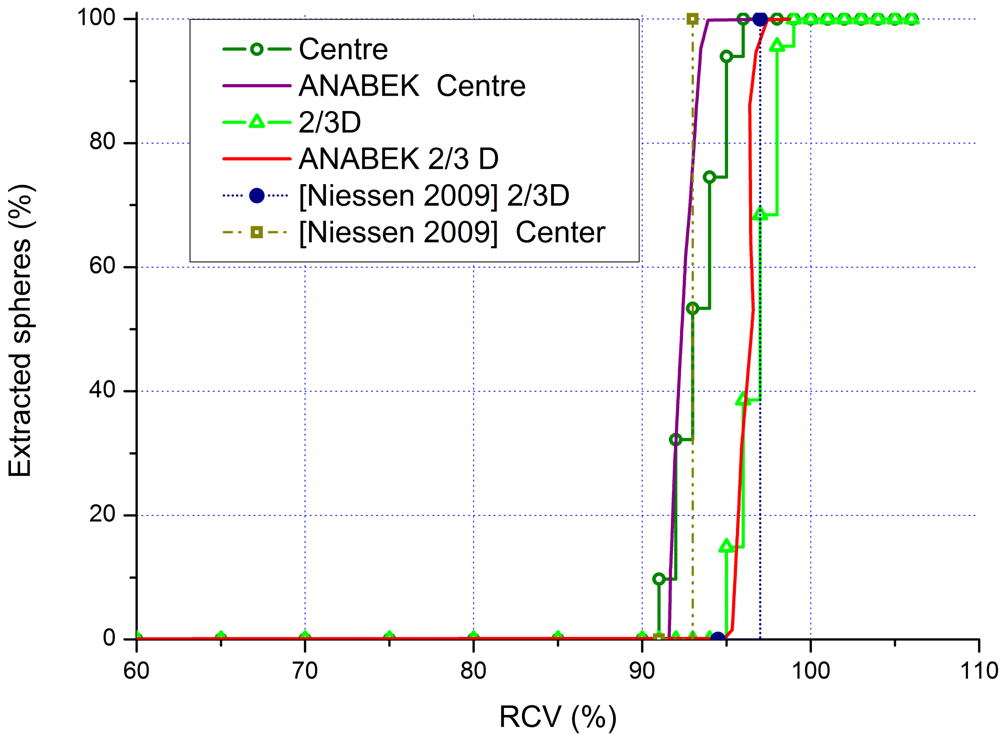

Figure F.20: RTD at surface core center and 2/3D. Comparison of the study case with D.E.M. simulations and ANABEK

The central region is studied injecting a small ring of tracking particles in the center of the core, and in a ring 2/3 D from the center of the vessel. The accuracy of the results compared in figure F.20 is high and confirms the assumptions taken about the low specific weight of forces between pebbles compared with wall effects.

The results of the whole core surface in figure F.21 show a very good accuracy level until the 95% of the marked pebbles have left. The 5% of the remaining pebbles correspond to those that flow close to the core reflector. This is the key point of this analysis. If the results of the pebbles injected at center and 2/3 D are summed up and compared with the whole surface results, it can be observed that the greatest part of the pebbles, leave within a small time interval. Therefore, the influence of the wall friction and long range forces is limited to a small distance.

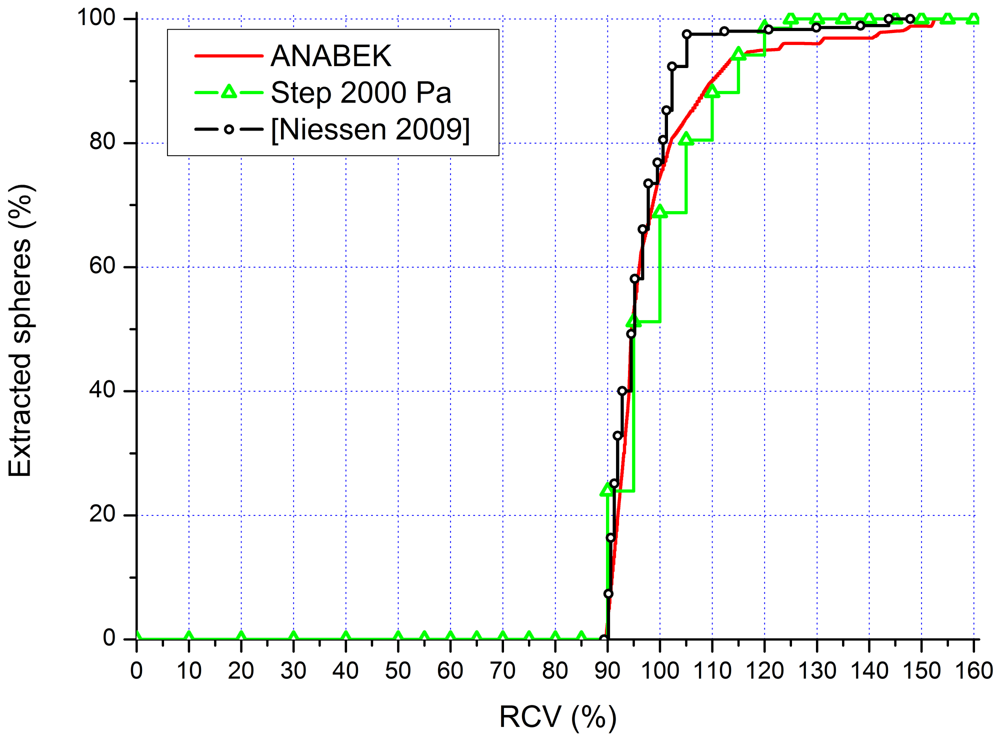

Figure F.21: RTD curves comparison of the best case with D.E.M simulations and experimental data

It was previously mentioned that the effects can be observed until five pebble diameters, which is a sensible distance taking into account the results. But despite that fact, the influence over the overall flow behavior is very high and it has not relation with the friction effects, but with the mass flow of pebbles. In case of very high shear stresses over the wall, the velocity at those locations is reduced. The mass flow condition defined at the outlet, therefore, faster velocity in the central region must compensate the friction effects.

F.4.2. Velocity profiles and streamlines

The direct comparison of the simulation results with ANABEK experiments is not possible because velocity was not measured in them, for this reason, in figure F.4, F.5,F.6, F.7 and F.8 there is a comparison with three different cases. It must be considered as a prediction of the velocity profiles.

Appendix G

CONCLUSIONS AND OUTLOOK

G.1. Conclusions of the pebble bed study

The study of a granular flow with a continuum framework requires the construction of a model that takes into account the most number of variables possible. During the development of the present work many assumptions had to be made due to the complexity of the system. However, after testing the most important simplifications made, it can be assessed that it does not suppose a large loss of accuracy for the final development of the model and that it is compensated by a more flexible, more simple and faster solution. As a conclusion, the most important facts confirmed during the research are here resumed.

The great number of variables which have to be reduced and the inherent differences between both systems entail a loss of accuracy but do not imply important changes of the flow behavior. The boundary conditions, specially in case of the wall boundary conditions, play the most important role for the proper coupling of both granular and fluid systems. In case of the wall boundary conditions, the influence of friction forces with the core reflector define the main characteristics of the flow behavior and for this reason, the knowledge and comprehension of their physical basis is essential.

The influence of the viscosity was much lower than expected. The influence over the flow is low compared with the forces over the reflector wall and for this reason, a virtual viscosity can be accepted. The saturation of viscosity and therefore the existence of a maximum shear rate has been proved in all the simulations performed.

Long range forces reach longer distances in case of viscous fluids than in pebble beds and is a negative consequence of the continuum approach. A no Newtonian viscous fluid was supposed to solve this problem but no evidences of that were found.

In the upper region mass flow was observed, but close to the transition region, the flow evolved to a funnel flow pattern. This fact implies large energy losses of the pebbles due to friction. No stagnant zones were detected, but very low velocity regions appeared in the transition region between core and hopper. Thus, the geometry of that region requires intensive research.

In case of the physical results it is confirmed that the study of flow lines and the flow regions match with good precision with the experiments performed in the past. The residence time distribution shows high precision for the first 95% of the pebbles in the simulations performed. Nevertheless, the results for the regions close to the reflector wall and hopper are not satisfactory, probably due to the irregularity of the pebble flow and all the difficulties that requires the comprehension of complex flows. The velocity profiles could not be compared with experimental data, despite of that fact and compared with the flow patterns, a good agreement can be supposed.

The possibilities of use in different reactor models are successful. Different calculations of different models were carried out. Nevertheless the lack of experimental data or empirical expressions leave uncertainty in the validity of the solution.

There is no a general formulation that can explain all the characteristics and the behavior of a granular flow, and therefore the development of continuum models is necessary in a middle future. The comprehension of the friction forces with the walls and the transmission mechanism of forces between pebbles requires still a lot of efforts.

G.2. Outlook

For the development of the present work and in order to achieve a better comprehension of pebble beds a whole experiment, in which all the flow characteristics, stress studies and material properties are studied, is required. The influence of the different reactor core regions is still not clear and especially an empirical analysis of the hopper would be also needed for an optimized vessel design.

According to the silo theory a precise expression for the horizontal and vertical pressures can be obtained by means of D.E.M. methods. However, experimental procedures should also be performed. This is also caused due to the high variability of the material properties under severe ambient conditions, monitoring the different working points of those materials within the core is required.

Different viscous models were tested during the project but with limited results. The better accordance was found for Bingham and pseudoplastic fluid models, but the lack of empirical information about this possibility made necessary to reject those viscous models. However, in the study field of soil mechanics appear this possibility and some experimental methods are proposed.

Like in case of Janssen's profile formula, a relation for the virtual viscosity with geometry, material properties and operation characteristics was discussed.

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