AN INTEGRATED SYSTEMS CFD SIMULATION OF A PEBBLE BED REACTOR

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ABSTRACT

The theoretical basis of a systems CFD model of a pebble bed reactor is discussed. This model is employed to simulate the thermal-fluid phenomena of the reactor core. The formulation of the fundamental equations results in a collection of one-dimensional elements that can be used to construct a network model of the reactor. One preliminary test is discussed to illustrate the application of the model.

INTRODUCTION

The Pebble Bed Modular Reactor (PBMR) power plant is currently being developed by PBMR (Pty) Ltd in South Africa in association with ESKOM and other industrial partners. This high temperature gas cooled reactor (HTGR) plant is based on a three-shaft Brayton cycle with helium gas as the coolant. The complexity associated with the thermal-flow design of the cycle requires the use of a variety of analysis techniques and simulation tools. These range from simple one-dimensional models that do not capture all the significant physical phenomena to large-scale three-dimensional CFD codes that, for practical reasons, can not simulate the entire plant as a single integrated model.

One of the most prominent codes that provide a suitable compromise is the thermal-flow integrated systems CFD or network simulation code Flownex [1]. Flownex allows detailed steady state and transient thermal-flow simulations of the complete power plant, fully integrated with core neutronics and controller algorithms. The reactor model for the integrated simulation currently consists of a point kinetic neutronics model combined with a simplified one-dimensional finite difference thermal-flow simulation of the reactor core.

This paper describes the theoretical basis and formulation of a more comprehensive reactor model capable of capturing the significant physical phenomena. The model is based on the fundamental equations for the conservation of mass, momentum and energy for the compressible fluid flowing through a fixed bed, as well as the equations for the conservation of energy for the pebbles and core structures. Through a rigorous analysis the equations are reduced and recast in a form that is suitable for incorporation in an integrated systems CFD code. This formulation of the equations results in a collection of one-dimensional elements (models) that can be used to construct a comprehensive multi-dimensional model of the reactor. The elements account for the pressure drop through the reactor; the convective heat transport by the gas; the convection heat transfer between the gas and the solids; the radiative, contact and convection heat transfer between the pebbles and the heat conduction in the pebbles. Despite the increased complexity it retains the simplicity of the network approach.

The application of the model is illustrated by calculating the buoyancy driven flow in an annular packed bed with heated walls.

THEORETICAL BACKGROUND

Due to the cylindrical shape of the reactor it is assumed that it is tangentially uniform and that the equations may therefore be expressed in axi-symmetric cylindrical coordinates. The equation for the conservation of mass for the fluid in a porous medium may then be expressed as

(1)

where is the porosity of the bed, the density of the fluid, the velocity in the radial direction and the velocity in the axial direction. The resistance of the pebbles to the flow through the reactor is accounted for via the Ergun correlation [2]. It can be shown that the dimensionless resistance force due the pebbles dominates the flow. The convective terms and the diffusive of shear stress terms in the momentum equations may therefore be neglected. The static pressure may also be converted to total pressure [3]. The equation for the momentum in the radial direction may then be written as

(2)

where is the velocity magnitude, the total temperature, the static pressure, the total pressure and the gravitational acceleration in the radial direction. Similarly the equation for the momentum in the axial direction may be written as

(3)

where is the gravitational acceleration in the axial direction. It can be shown that the contributions of viscous dissipation is negligible compared to other the terms in the energy equation. The equation for the conservation of energy for the fluid in terms of the total specific enthalpy is then given as

(4)

where is the thermal conductivity of the gas. In the case of the solids three energy equations can be distinguished, that is, the conduction in the pebbles, the heat transfer between the pebbles and the conduction in the reflector blocks. It is assumed that the temperature distribution in a pebble is the same in all radial directions. The equation for the conservation of energy in a pebble can therefore be written in one-dimensional spherical coordinates as

(5)

where is the specific heat capacity, the absolute temperature and is the heat generated in the pebble. The heat transfer between the surfaces of the pebbles due to contact, convection and radiation can be written in axi-symmetric cylindrical coordinates as

(6)

where k_{eff} is the effective conductivity that accounts for the abovementioned effects. The Zehner-Schlünder correlation [2] is employed to determine the effective conductivity k_{eff} between the pebbles. It is as a first approximation assumed that this correlation can also be used to determine the heat transfer between the pebbles and the reflector blocks.

The equation for the conservation of energy in the (porous) reflector blocks is given in axi-symmetric cylindrical coordinates as

(7)

where is the heat generated in the reflector blocks.

The solution of the abovementioned conservation equations for a particular problem can be obtained subject to the necessary boundary conditions being specified. Three sets of boundary conditions can be distinguished. The first set of boundary conditions occur at the inlet and outlet boundaries and links the reactor flow and temperature fields to the flow and temperature fields of the power conversion unit (PCU). These boundary conditions are specified implicitly through the requirement that the flow and temperature fields at the interfaces between the reactor and the PCU must be continuous. The second set of boundary conditions occurs at the walls of the pressure vessel and deals with the heat transfer from the reactor to the surroundings through convection and radiation. The third set of boundary conditions deals with the heat transfer at internal interfaces such as between the pebbles and the gas, between the walls of the reflector blocks and the gas, between the walls of the inlet and outlet passages and the gas, and between the pebble surfaces and the walls of the reflector blocks. These boundary conditions in particular link the conservation equations for energy for the fluid and the solids / pebbles to each other. These heat transfer mechanisms enter equations (4) to (7) when they are integrated over the control volumes.

The correlation for the surface heat transfer coefficient proposed by Kugeler *et al.* [2] is used to determine the heat transfer between the pebbles and the coolant. It is as a first approximation assumed that this correlation can also be applied for the heat transfer between the coolant in the core and the reflector blocks. The heat transfer between gas flowing through the inlet and outlet holes and the reflector blocks is determined using the well-known Dittus-Boelter relationship.

A scrutiny of equations (1) to (7) reveal that they are one-dimensional, or that they can be written as the sum of two one-dimensional equations. This formulation of the equations allows the packed bed reactor to be discretized into a collection of one-dimensional elements (models) that can be incorporated with ease in a general network approach [3]. This then makes it possible to incorporate the model of the reactor in the systems CFD code Flownex [1].

EXAMPLE

To ensure the applicablity of the numerical model the validity of the heat transfer correlations must amongst other be thoroughly tested. The SANA test facility [4], [5] was constructed at the Research Centre Jülich to investigate the heat transport phenomena inside the core of a high temperature gas cooled reactor. The test facility consisted of a cross section of a heated cylindrical pebble bed inside a furnace to simulate the thermal conditions of such a HTGR core. A large number of steady-state and transient experiments were carried out. The main parameters that were varied were the pebble material, pebble diameter, cooling gas, heating geometry and heating power. Due to the wide range of these variations, the database can be used for code validation and for general research on porous media. The experiment also demonstrated that a HTGR can be design in such a way that in the case of the loss of all active cooling systems the temperatures can be controlled passively through conduction and bouyancy driven convective transport. At no time temperatures will occur that may result in damage to the fuel spheres or the release of fission products from the fuel elements. It is intended to use a selection of these results to test the numerical model.

However, not all the correlations that are required can be extracted from the SANA experiment. The proposed PBMR pebble core will be an annular core with a solid central column. A test facility similar to the SANA test facility is therefore currently being under consideration. The test facility will have an annular packed bed representative of a slice from the PBMR reactor core. The test facility will not only be used to investigate the heat transport phenomena inside the core of an annular high temperature gas cooled reactor in a way similar to the SANA experiment, but will also be used obtain the correlations that can not be extracted from the SANA database.

It is proposed that the test facility consists of annular bed with an inside diameter of 0.6 m, an outside diameter of 2.3 m and a height of 1.2 m. The inside wall will be heated and the outside wall will be cooled by means of water jacket. The upper and lower surfaces will be insulated to be adiabatic. The packed bed will consist of graphite spheres with a diameter of 60 mm.

Some preliminary simulations using the proposed geometry have been executed to get an indication of the performance of the numerical model. In the first case that was considered it was assumed that a vacuum existed. No convection transfer and convective transport will take place and the heat will therefore only be transferred through conduction, contact and radiation.

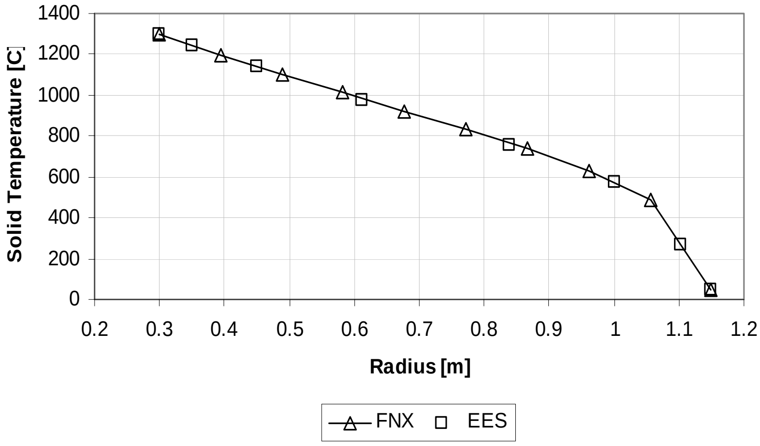

Figure 1: Temperature distribution in packed bed due to conduction, contact and radiation only.

Figure 1 shows the temperature distribution in the spheres in the radial direction under steady-state conditions. The temperature of the inner wall was assumed to be 1300 °C, whilst the temperature of the outer wall as assumed to be 50 °C. The results obtained with Flownex are compared with the results obtained from a model that was programmed in the EES engineering equation solver. It can be seen that the agreement is good and it can therefore be concluded that the model was implemented correctly in Flownex. However, a further set of comprehensive tests will have to be performed before it can be confirmed that the model was implemented correctly.

In the second case that was considered the voids in the packed bed was assumed to be filled with helium. The inner wall was again taken to be at a temperature of 1300 °C and the outer wall to be at a temperature of 50 °C. The temperature difference between the inner wall and the outer wall resulted in the well-known buoyancy driven recirculating flow pattern developing. The gas moved up along the inner wall as it was heated and down the outer wall as it was cooled.

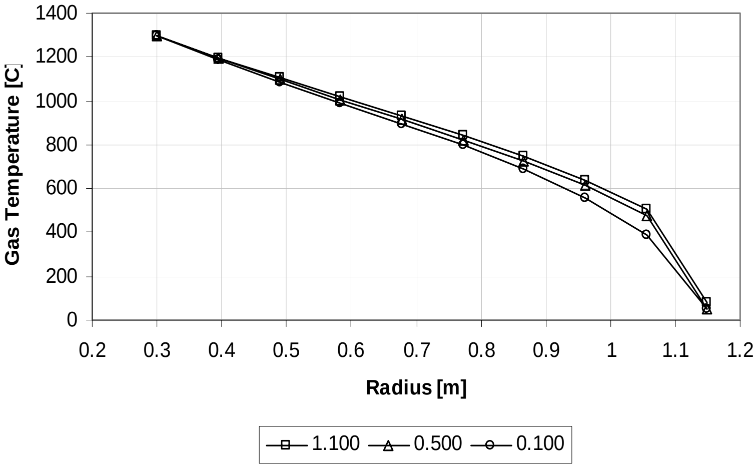

Figure 2: Radial distribution of gas temperature at selected axial positions in annular bed.

Figure 2 shows the radial distribution of the gas temperature at axial distances of 0.10 m, 0.50 m and 1.10 m above the bottom of the annular bed. Along the inner wall the gas temperature is almost uniform. However, towards the outer wall it can be seen how the gas is cooled as it moves down to the bottom.

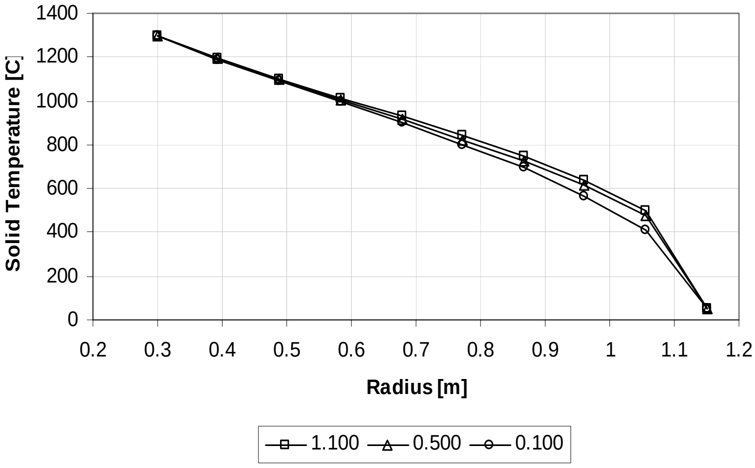

Figure 3: Radial distribution in packed bed at selected axial positions in annular bed.

Figure 3 shows the radial distribution of the temperature in the packed bed at axial positions of 0.10 m, 0.50 m and 1.10 m above the bottom of the annular bed. A comparison of the gas temperatures and the packed bed temperatures indicate that main heat transfer mechanism is the conduction, contract and radiation heat transfer through the packed bed. It can be seen, however, how the temperatures in the packed bed are also affected by the gas recirculating through the bed. The observations are in qualitative agreement with results that had been obtained in the SANA experiment.

CONCLUSIONS

The theoretical basis of a systems CFD model of a pebble bed reactor was discussed. This model is employed to simulate the thermal-fluid phenomena of the reactor core. The formulation of the fundamental equations results in a collection of one-dimensional elements that can be used to construct a network model of the reactor.

Two sets of preliminary results were discussed. In the first case the radial distribution of the temperature due to conduction, contact and radiation in the packed bed under vacuum condtions was shown. The results are in good agreement with a set of results that had obtained from a model that was pogrammed in the EES engineering equation solver. In the second case it was assumed that the voids in the packed bed were filled with helium. The radial distributions at selected axial positions of the gas temperature due to convection and buoyancy driven convective transport, and the temperature in the packed bed due to conduction, contact and radiation were shown. These results are in qualitative agreement with those obtained in the SANA experiment.

It can be concluded that the model was implemented correctly in Flownex. However, further comprehensive tests will have to be performed before it can be finally confirmed that the model was implemented correctly and before it can be considered to be properly validated.

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