Proceedings of the 18th International Conference on Nuclear Engineering
ICONE18
May 17-21, 2010, Xi'an, China

ICONE18-29172

INVESTIGATION OF PRESSURE DROP FOR FLUID FLOW THROUGH POROUS MEDIA: APPLICATION TO A PEBBLE-BED REACTOR

Xiaoyu CAI[1,2],
Email: kiplincai@gmail.com
Suizheng QIU[1, 2]*,
Tel: +86-29-82665607
Fax: +86-29-82665607
Email: szqiu@mail.xjtu.edu.cn

Guanghui Su[1, 2],
Email: ghsu@mail.xjtu.edu.cn
Wenxi Tian[1,2],
Email: wxtian@mail.xjtu.edu.cn

[1] State Key Laboratory of Multiphase Flow in Power Engineering, Xi’an Jiaotong University, Xi’an 710049, China
[2] School of Nuclear Science and Technology, Xi’an Jiaotong University, Xi’an, Shaanxi 710049, P R China

ABSTRACT

The present studied Pebble-Bed Reactor is a light-water cooled reactor that consists of millions of Micro-Fuel Elements, and the TRISO-coated fuel particles(MFE) fill the fuel assembly disorderly and form a porous media with internal heat source. Papers on porous media continue to be published at the rate of about 150 per year and the domain of application is wide spread, ranging from chemical particle beds, mass separator units, debris beds, soil investigations, heat pipes and fluidized beds etc.

In this paper, investigation is performed on the press drop under conditions of both single-phase and two-phase flow through porous media. Large number of relations are studied and the relational expressions, which generalize the available data of experiments, are suggested for pressure drop calculation in a pebble bed of spheres at random distribution. Finally, the relational expressions are applied to analyze the flow characteristics of the Pebble-Bed Reactor, such as the influence of pressure on two phase friction factor in the core etc.

Key Words: pebble-bed reactor, porous media, pressure drop, Micro-Fuel Elements

INTRODUCTION

The pressure drop accompanying the flow of fluids through porous media has been the subject of theoretical analysis and experimental investigation for decades. Much work has been carried out on the subject and numerous papers publish every year.

The purpose of the present paper is to summarize the existing information and to verify the empirical or semi-empirical correlations presented earlier. So a large number of correlations were studied theoretically and compared by developing a code. Finally these recommended proper correlations were applied to a new type pebble bed reactor.

The results of present study may be of interest to engineers or individual team members to develop programming and may help to increase programmer productivity.

The Main design features of a new type pebble bed water cooled reactor with Micro-Fuel Elements are presented in this paper. The water and steam circulation inside the vessel by means jet pump is shown in Fig 1.The coolant water with a initial temperature 240℃ is injected into the core by the pump. After absorbing great amount of heat, it goes through liquid region to vapor–water two-phase region and finally becomes about 550℃ single phase steam at the outlet. The reactor core is arranged like Fig.2. There are totally 145 fuel assemblies in-line triangular pitch in the core. The fuel assembly is manufactured with a steel-walled tube. Water is used as coolant that flows from bottom to top through the tube, thereby fluidizing the particle bed, while the moderator water flows in the reverse direction out of the tube. Each fuel assembly consists of about 1.0E5 Micro-Fuel Elements (as shown in Fig.3). The MFE is a TRISO-coated fuel particle as shown in Fig.4. Micro-Fuel Elements fill the fuel assembly disorderly and form a porous structure.

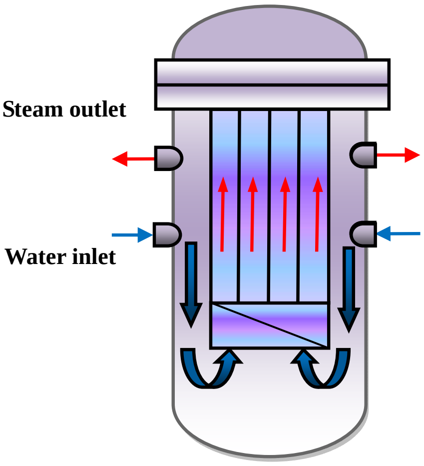

Fig.1.Scheme of water and steam circulation inside the vessel by means jet pump

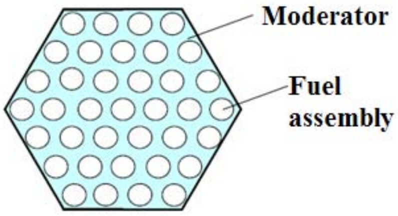

Fig.2.Scheme of reactor core arrangement

Fig.3.Schematic diagram of a fuel assembly

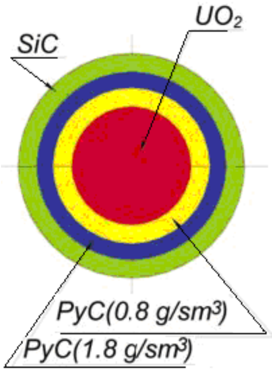

Fig.4. Design scheme of Micro-Fuel Elements

NOMENCLATURE

De	effective diameter, m
d_p	particle diameter, m
f	friction factor
g	gravitational acceleration, m^2/s
h	heat transfer coefficient, W/m^2 K
H	enthalpy , J/kg
j	superficial velocity, m/s
L	bed height, m
P	pressure, Pa
Q	heat flux, W/m^2
r	radial distance, m
Re	Reynolds number, $\rho j\, d_p/\mu$
Re_p	pore Reynolds number
S	slip ratio, dimensionless
T	temperature, °C
ΔT	temperature difference, °C
T_f	average temperature of fluid, °C
T_s	MFE surface temperature, °C
U	the heating perimeter, m
W	mass flow rate, kg/s
x	equilibrium vapor mass quality, dimensionless
	Greeks
ε	porosity, dimensionless
ρ	density, kg/m^3
α	void fraction, dimensionless
μ	dynamic viscosity, kg/m s
ν	kinematic viscosity, m^2/s
	Superscript/Subscript
c	clad
f	Fluid coolant
g	gas
l	liquid
u	fuel
s	saturated
w	wall
TP	Two Phase

1 MATHEMATICAL AND PHYSICAL MODELS

The core of the reactor under research is made up of 145 fuel assemblies totally. There are no mass, momentum or energy exchanging among them. Therefore, one assembly(Fig.3) was chosen and the single-channel model was applied. The radial temperature difference is negligible, so we treat it a one-direction flow and heat transfer through a porous structure.

1.1 Mathematical model

For the equilibrium core, the steady-state flow of the fluids through columns packed with granular material is governed by the following equations:

The mass conservation equation:

$$\frac{dW}{dz}=0 \tag{1}$$

The momentum conservation equation:

$$-\frac{dp}{dz}=\frac{d}{dz}\left(\frac{W^2}{\rho A^2}\right)+\frac{dp_f}{dz}+\rho g \qquad (2)$$

And the energy conservation equation:

$$W\frac{dH}{dz}=qU \qquad (3)$$

Where, W is the mass flow rate calculated by the superficial velocity j and $dp_f\,/\,dz$ is the friction pressure drop that will be further discussed in the following text detailedly.

Fig.4 demonstrates the physical model of the micro fuel elements. The MFE is a TRISO-coated fuel particle. The UO_2 fuel kernel of particles is coated by ceramic layers, namely the inner buffer layer with less dense pyro-carbon, the dense pyro-carbon, and the outer layer SiC coating.

1.2 Single phase flow friction models

Many investigators have studied the single phase flow in porous media, but the final results differ greatly. The detailed expressions of these correlations were shown in Table 1.

Where, $\mathrm{Re}=\frac{\rho j d_p}{\mu}$, $\mathrm{Re}_p=\frac{\rho j d_p}{\mu(1-\varepsilon)}$

1.3 Two phase flow friction models

The study of two phase flow through porous media has been the focus of interest of many recent studies. Two typical flow friction correlations for two phase flow are shown in the following Table 2, the others can be found in the references[11-15].

1.4 Thermophysical property model

The accurate coolant thermophysical property model is one of the key factors for successful simulation. The thermophysical property correlations of the coolant used in this study were chosen from the international standard (Rhosenow and Hartnett, 1973). Comparison between the model prediction and the IAPWS-IF97 standard has been conducted to verify and extend the applicability of those models under low pressure condition.

1.5 Calculation parameters

The main initial calculation parameters of the Micro-Fuel Elements and fuel assembly are shown in the following Table 3.

It should be pointed out that there is no heat source within the porous structure for the single phase flow. But for two phase flow, the average power density is about 1.6E8 W/m^3 .

Table 1: Flow friction correlations for single phase flow

NO	**Investigators**	**Correlations**	**Range of application**
1	Ergun，1952[1]	$\frac{\Delta p_f}{L}=150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu j}{d_p^2}+1.75\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho j^2}{d_p}$	$\frac{\mathrm{Re}}{1-\varepsilon}=1\sim 2000$
2	Rose, 1945[2]	$f=1000\,\mathrm{Re}_p^{-1}+60\,\mathrm{Re}_p^{-0.5}+12$	$--$
3	Rose and Rizk, 1949[3]	$f=1000\,\mathrm{Re}_p^{-1}+125\,\mathrm{Re}_p^{-0.5}+14$	$--$
4	Kuerten, 1966[4]	$f=\left(\frac{6.25}{\varepsilon^3}(1-\varepsilon)^2\right)\left(21\mathrm{Re}_p^{-1}+6\,\mathrm{Re}_p^{-0.5}+0.28\right)$	$1\le \mathrm{Re}_p\le 4,000$
5	Hicks, 1970[5]	$f=6.8\frac{(1-\varepsilon)^{1.2}}{\varepsilon^3}\mathrm{Re}_p^{-0.2}$	$500\le \mathrm{Re}_p\le 60,000$
6	Tallmadge, 1970[6]	$f=\frac{150}{\mathrm{Re}_p}\frac{(1-\varepsilon)^2}{\varepsilon^3}+\frac{4.2(1-\varepsilon)^{1.166}}{\varepsilon^3}\mathrm{Re}_p^{-1/6}$	$0.1\le \mathrm{Re}_p\le 100,000$
7	Sug Lee and Ogawa, 1974[7]	$f=\left(\frac{6.25}{\varepsilon^3}(1-\varepsilon)^2\right)\left(29.32\,\mathrm{Re}_p^{-1}+1.56\,\mathrm{Re}_p^{-n}+0.1\right)$ *with* n=0.352+0.1ε+0.275ε^2	$1\le \mathrm{Re}_p\le 100,000$
8	Montillet, 2007[8]	$f=0.061\left(\frac{1-\varepsilon}{\varepsilon^3}\right)\left(\frac{d_c}{d_p}\right)^{0.2}\left(1000\mathrm{Re}_p^{-1}+60\mathrm{Re}_p^{-0.5}+12\right)$	$10\le \mathrm{Re}_p\le 2,500$
9	Avdeev, 2008[9]	$f=\frac{3.56}{\varepsilon^{3.8}}\frac{1}{\mathrm{Re}^{0.2}}$	$250\le \mathrm{Re}\le 6.5\times 10^3$
		$f=\frac{0.615}{\varepsilon^{3.8}}$	$\mathrm{Re}\ge 6.5\times 10^3$

Table 2: Two typical flow friction correlations for two phase flow

NO	**Investigators**	**Correlations**	**Range of application**
1	Sorokin, 2007[10]	$\left(\Delta p/L\right)_{ftp}=\left(\Delta p/L\right)_{fl}\Phi_l^2$ $\Phi_l^2=1+C/X+1/X^2$ $\left(\Delta p/L\right)_{ftp}=\left(\Delta p/L\right)_{fg}\Phi_g^2$ $\Phi_g^2=1+CX+X^2$	$X^2=\left(\Delta p/L\right)_{fl}/\left(\Delta p/L\right)_{fg}$ $C=\left[\left(\rho_l\sigma 1.5\frac{1-\varepsilon}{\varepsilon^3 d_p}\right)\Big/\left(180\frac{(1-\varepsilon)^2}{\varepsilon^3 d_p^2}\mu_l G d_p\right.\right.$
2	Avdeev, 2008[9]	$\frac{\Delta P_{ftp}}{\Delta P_f}=\frac{1}{1-0.83a_0\left(1-\frac{\rho_g}{\rho_l}\right)}$	$a_0<0.8$
		$\frac{\Delta P_{ftp}}{\Delta P_f}=\frac{1}{1-\left(1-\frac{\rho_g}{\rho_l}\right)\frac{1}{\sqrt{1+6.25(1-}}}$	$a_0\ge 0.8$

Table 3: Main parameters of the fuel assembly and MFE

Name	Unit	Value
Pressure	Mpa	10
Inlet water temperature	℃	240
Inlet flow rate	kg/s	0.16
Height of the fuel assembly	m	0.7
Internal diameter of the fuel assembly	m	0.07
Diameter of the MFE	mm	3
Porosity(the ratio of void to total volume)	dimensionless	0.36

2 RESULTS AND DISCUSSIONS

Fig.5 shows that single phase friction pressure drop increased when Reynolds number increased. All the results were quite close to each other at low Reynolds number, but as Reynolds number increased, Darcy, Leva and Sug correlations' results are considerably lower than what was predicted by other correlations. This is because the kinetic energy dissipation can't be ignored as flow velocity is high enough.

Ergun equation considered varieties of effected factors in the field porous media, such as flow velocity, fluid properties, particle shapes, and so on. So it was widely used to calculate the single phase pressure drop. Refer to Avdeev correlation, his investigated object was quite similar to the present investigation, so the two typical results were compared with Liu's experiment results, as shown in Fig.6.a.

Fig.6.b may help to validate the present models. Typical results are compared by the ratio between the calculated results to Liu's experiment. At the inlet flow rate, viz. Reynolds number is 1252, the ratio of Ergun's result to Liu's is 1.31, and the difference increases with the Reynolds number increasing. While the difference between Avdeev and Liu's experiment is much smaller, the maximal ratio is about 1.07.

Fig.7 illustrates the proportion of friction is quite low at small Reynolds number, but for the present investigated object, the proportion is about 0.7 at inlet flow rate.

There has been many studies on the subject of two phase flow through porous media without heat source, such as: chemical packed bed, and a number of investigators have reported on severe accident in PWR, such as Dhir's investigation on core debris. Few researchers (Sorokin,2007; Avdeev,2008) have presented a quantitative data on two phase fluid flow for the pebble bed reactor with internal heat source. The results are shown in Fig.8. It can be observed that the result of Avdeev equation is 0.1MPa/m and that of Sorokin's is 0.16MPa/m.

The calculation and experiment results are shown in Fig.9. The difference between them is less than 25%, so Avdeev correlation is recommended for the present investigated object, viz. water-steam mixture concurrent up flow in pebble beds with internal heat source.

Fig.10 shows that the influence of pressure on two phase friction factor. It can be seen that two phase friction factor increases while the mass quality increases and at the same mass quality, the friction factor increases greatly with the pressure decreasing.

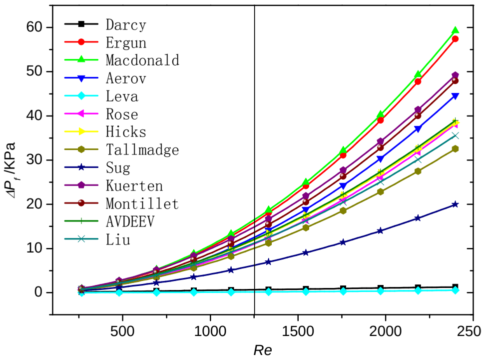

Fig.5. Friction pressure drop related to Reynolds number

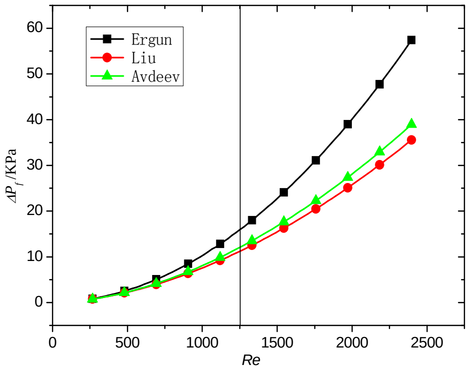

Fig.6.a Comparison of typical results

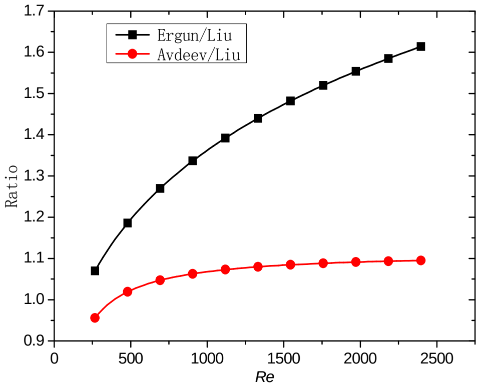

Fig.6.b Comparison of typical results to Liu's experiment

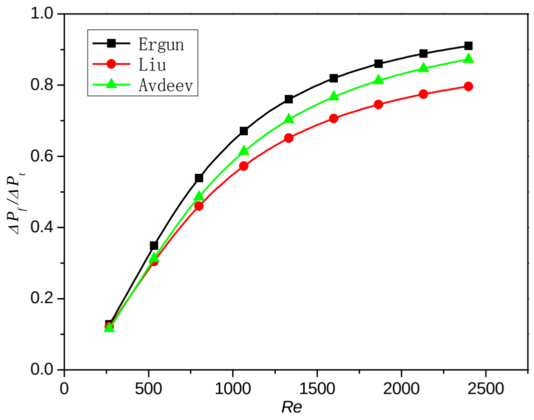

Fig.7 Proportion of friction to total pressure drop

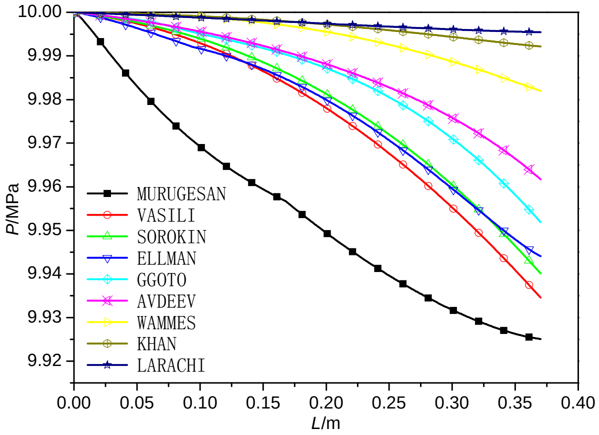

Fig.8 Two phase friction pressure drop along the flow direction

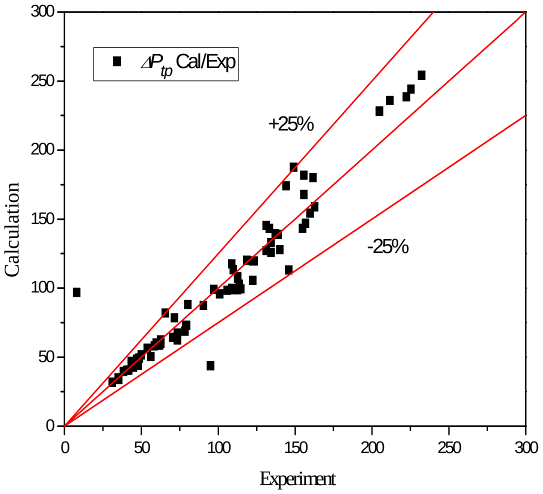

Fig.9 Validation of Avdeev correlation

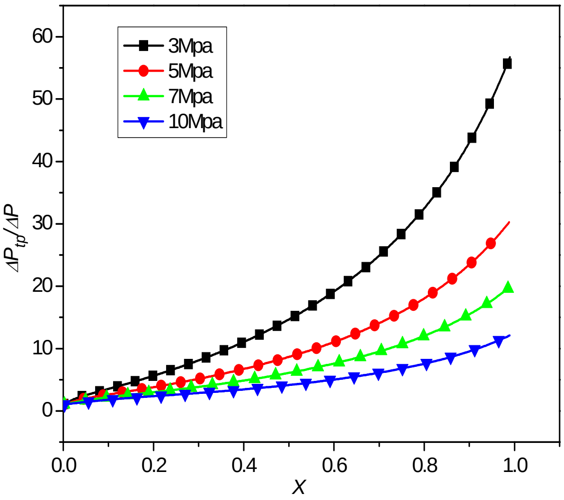

Fig.10 Influence of pressure on two phase friction factor

3 CONCLUSIONS

Based on the fundamental conservation laws and some suitable constitutive correlations used in porous media, investigation has been performed to verify a great number of empirical or semi-empirical correlations which are adopted to calculate single or two phase pressure drop in porous media. Several correlations were recommended to calculate pressure drop of single or two phase flow through a pebble bed reactor: Ergun, Avdeev and Liu's correlations for single phase flow; Sorokin and Avdeev correlations for two phase flow.

Furthermore, the final results indicated that a pebble bed reactor has a great pressure loss, about 0.1MPa/m for two phase flow.

To verify and valid the code, more experiment data are essential, and the project is under preparation. We are going to continue our study for those problems.

ACKNOWLEDGMENTS

This project was financially supported by Nuclear Power Institute of China (NPIC).

REFERENCES

[1] Ergun S. Fluid flow through packed columns[J]. Chemical Engineering Progress, 1952, 48: 89–105.

[2] Rose H.E. On the resistance coefficient－Reynolds number relationship for fluid flow through beds of granular materials[J]. Proceedings of the Institution of Mechanical Engineers, 1945, 153: 154－161.

[3] Rose H.E, Rizk A.M.A. Further researches in fluid flow through beds of granular material[J]. Proceedings of the Institution of Mechanical Engineers, 1949, 160: 493－503.

[4] Kürten H, Raasch J, Rumpf H. Beschleunigung eines kugelförmigen Feststoffteilchens im Strömungsfall konstanter Geschwindigkeit[J]. Chemical Engineering and Technology, 1966,38 (12): 941 – 948.

[5] Hicks R.E. Pressure drop in packed beds of spheres[J]. Industrial and Engineering Chemistry Fundamentals, 1970, 9 (3): 500 – 502.

[6] Tallmadge J.A. Packed bed pressure drop — an extension to higher Reynolds numbers[J]. AIChE Journal, 1970, 16 (6): 1092 – 1093.

[7] Sug Lee J, Ogawa K. Pressure drop through packed beds[J]. Journal of Chemical Engineering of Japan, 1974, 27 (5): 691 – 693.

[8] Montillet A, Akkari E, Comiti J. About a Correlating Equation for Predicting Pressure Drops through Packed Beds of Spheres in a Large of Reynolds Numbers[J]. Chemical Engineering and Processing, 2007, 46: 329–333.

[9] Avdeev A.A, Soziev R.I. Hydrodynamic Drag of a Flow of Steam–Water Mixture in a Pebble Bed [J].High Temperature, 2008, 46 (2): 223–228.

[10] Sorokin V. V. Calculation of Two-Phase Adiabatic Flow in a Pebble Bed[J]. High Temperature, 2007, 45 (2): 227–232.

[11] Larachi F, Laurent A, Midoux, N, et al. Experimental study of a trickle-bed reactor operating at high pressure: two-phase pressure drop and liquid saturation[J]. Chem. Engng Sci, 1991, 46: 1233-1246.

[12] Khan A., Khan A.A, Yelamanchili Y.B.G. Prediction of Two-Phase Frictional Pressure Drop for the Concurrent Gas and Newtonian Liquids Upflow through Packed Beds[J]. Chem. Eng. Technol, 2002, 25 (1): 51-55.

[13] Wammes, W.J.A, Middelkamp J, Huisman W.J, et al. Hydrodynamics in a cocurrent gas-liquid trickle bed at elevated pressures[J]. A.I.Ch.E. J, 1991, 37: 1849-1862.

[14] Ellman M.J, Midoux N, Wild G, et al. A new improved liquid hold-up correlation for trickle-bed reactors[J]. Chem. Engng Sci, 1991, 45: 1677-1684.

[15] Liu, X.-Q., X. Yan, and Z.-J. Xiao, *Resistance characteristics of single-phase flow through porous media.* Hedongli Gongcheng/Nuclear Power Engineering, 2009. 30(5): p. 40-43.