Pressure Drop Experiments on a Flow Channel Filled with Catalysts for Nuclear Hydrogen Production System

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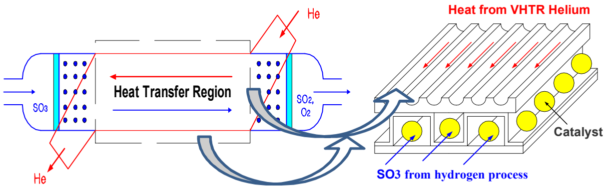
1. Introduction

Designing a process heat exchanger (PHE) is one of the main technical challenges in the development of a nuclear hydrogen production system. The PHE provides an interface between the helium gas and the sulfuric acid gas. The Korea Atomic Energy Research Institute (KAERI) has developed a hybrid-design decomposer to withstand severe operating conditions [1]. Fig. 1 shows the layout of the PHE. The SO3 flow channels are catalyst channels that have enough space to be filled with 1-4mm diameter catalysts. Hong and Seo [2] have been studying a two-dimensional numerical analysis for a catalyst channel line-up with a 3mm ball shaped catalyst. They compared their CFD results to many widespread correlations developed for porous media such as those by Carman, Ergun, and Zhavoronkov as well as Susskind & Becker and Reichelt [3-7] including a pebble-bed nuclear reactor design correlation, the KTA correlation [8]. They reported that there is much discrepancy in predicting the pressure drop between the existing correlations and the channel pressure drop obtained from their two-dimensional CFD analysis. The main reason for this is considered to be a discord of the channel geometry and an extreme irregularity in the size of the catalyst. They concluded that the validation should be accomplished by the experiments for a catalyst channel simulating the channel of the PHE.

In this paper, we discuss the pressure drop experiments on a flow channel filled with ball shaped catalysts. The test section simulates a single channel of the PHE secondary side plate-fin channel. The experimental results compared well with the known pressure drop correlations and a numerical analysis, respectively.

2. Process Heat Exchanger

The process heat exchanger (PHE) developed in KAERI provides a hybrid type of flow channel geometry; there is a printed-circuit form on the primary helium side and a plate-fin form on the secondary SO3 side (Fig. 1). The SO3 gas is heated and decomposed into SO2 and O2 in the PHE. In the manufacturing process of a 10kW PHE, the secondary SO3 side is coated with a silicon carbide material using an ion-beam-mixing method in a vacuum chamber before assembly into a single block using diffusion bonding [9].



(a) Heat exchanger (b) Catalyst channel

Fig. 1. Hybrid type process heat exchanger

Ion-beam-mixing is a process in which the bombardment of a solid with a beam of energetic ions causes an intermixing of the atoms of two separate phases that were originally present in the near-surface region.

3. Pressure Drop Analysis

3.1 Pressure Drop in a Porous Media

The pressure drop in a channel is defined as follows;

$$\Delta p = \varphi \frac{L}{d_h} \frac{\rho V^2}{2}, \qquad (1)$$

In the case of porous media filled with pebble (or catalyst), the hydraulic diameter d_h depends on the porosity and pebble diameter(d_p) as,

$$d_h = d_p \left(\frac{\varepsilon}{1-\varepsilon}\right), \qquad (2)$$

where ε is the porosity (void fraction) in the bed

$$\varepsilon = \frac{V_{void}}{V_{bed}}.$$

Then the pressure drop in a porous media can be rewritten as follows;

$$\Delta p = \varphi \frac{L}{d_p} \frac{\rho V^2}{2} \left(\frac{1-\varepsilon}{\varepsilon}\right), \qquad (3)$$

3.2 Empirical Correlations

The only unknown parameter in equation (3) is the pressure loss coefficient, φ. There are many empirical correlations on the pressure loss coefficient developed at both the regular packing beds and the irregular packing beds (Table I). Carman [3] proposed a correlation of the pressure loss coefficient for the regular packing base as;

$$\varphi = \frac{6^{3-n}k}{Re_p^{3-n}} \frac{(1-\varepsilon)^{3-n}}{\varepsilon^3} \qquad (4)$$

When n = 1 and k = 5.

Susskind & Becker [6] updated the Carman correlation on considering an inertia effect of flow. The irregular packing comes from different size of packed material. The following correlation from Zhavoronkov et al. [5] is based on an irregular packing configuration with considering wall effect.

$$\varphi = \frac{A}{Re_p} \frac{(1-\varepsilon)^2}{\varepsilon^3} + B\frac{1-\varepsilon}{\varepsilon^3} \qquad (5)$$

Where,

$$A = 165.36A_w^2,\ B = 1.2B_w$$

$$A_w = B_w = 1 + \frac{1}{2(\frac{D}{d_p})(1-\epsilon)}$$

After removing wall effect, Ergun [4] simplified the parameter A and B in Equation (5) to the constant A=150 and B=1.75, respectively.

Table I: Characteristics of Empirical Correlations.

Correlation	Packing shape	Wall effect	Inertia effect
Carman	Regular	No	No
Susskind & Becker	Regular	No	Yes
KTA	Regular	No	Yes
Ergun	Irregular	No	Yes
Zhavoronkov et al.	Irregular	Yes	Yes
Reichelt	Irregular	Yes	Yes

3.3 Computational Modeling and Analysis

Two-dimensional unstructured grids are produced for a flow channel, 600mm in length and 4.5mm height as shown in Fig. 2. The channel filled with 3mm diameter ball-shaped catalysts. To avoid the generation of poor quality mesh cells from every contact points between catalysts, we assumed that all catalysts are line-up evenly in the middle of the flow channel with a 2% reduction in size compared to the original size. The major information of the computational model is as follows,

1. A total of 1,559,754 nodes is generated for numerical simulation
2. Nitrogen gas is used as a fluid medium instead of SO3 gas and defined to be incompressible
3. The flow regime covers a laminar flow, but we used $k-\epsilon$ turbulence model for all flow regimes in the analysis
4. A standard wall function is used with a smooth wall option
5. The wall temperature of 200 ℃ is given as a boundary condition

The model is implemented in a commercial *computational fluid dynamic* package, a CFX-13.0 [10]. The pressure loss coefficient in equation (1) is determined from the pressure drop obtained by the numerical model as,

$$\varphi = \frac{\Delta P}{L} \frac{2d_p}{\rho V^2} \left(\frac{\varepsilon}{1-\varepsilon}\right). \qquad (5)$$

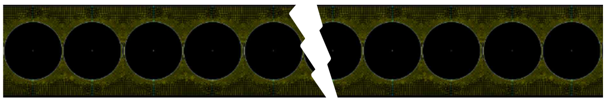
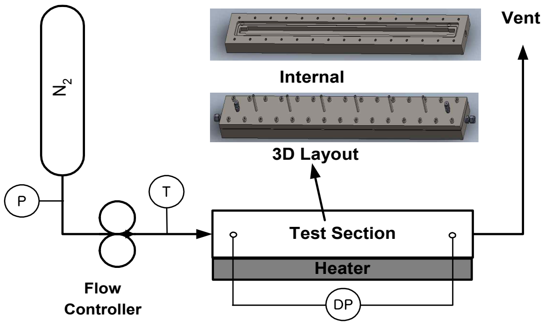


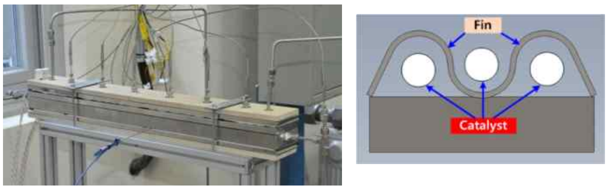
Fig. 2. Two-dimensional meshes for numerical analysis

4. Experimental Setup

We are preparing an experimental apparatus to measure the pressure drop on a PHE catalyst channel. The apparatus is composed of a Nitrogen supply tank, a test section, a mass flow controller (MFC), a pressure transmitter and a data acquisition system as shown in Fig. 3. The test section is designed to simulate the PHE secondary side catalyst channel. The catalyst channel is formed at 600mm in length with 4.5mm in height in the internal of a stainless-steel rectangular bar. The cover of the test section is bolted to replace the various sizes of the catalysts conveniently.



(a) Layout of experimental device



(b) Test section (c) Channel cross section

Fig. 3. Experimental setup for catalyst channel

5. Results and Discussion

The catalyst channel in PHE belongs to the regular packing configuration. It expected strong wall effect by the form of narrow channel. At the regular geometry, higher local velocities are observed near the wall due to a significant local void fraction there. This channeling effect (or confining wall effect) in regular packing enables gas to flow smoothly throughout the entire bed. This induces that the regular packing produce a lower pressure drop than those of irregular packing at the point of the same average void fraction. This effect is well represented quantitatively to the Fig. 4 in comparison of various correlations on both regular and irregular packing beds; The results of irregular based correlations calculates the pressure drop higher than regular based correlations. The pressure drop of 2D CFD analysis on 3mm diameter catalyst lies in the middle in the pressure drops of empirical correlations (Fig. 4(a)). But all of the correlations including CFD analysis predict the pressure drop less than those of the experimental value. The main reason for this is considered that the catalyst channel has a very narrow and wavy form. Another reason is considered to the large void fractions (ε = 0.79) of 3mm catalyst channel which is beyond the application range on void fraction in the correlations. The latter one is backed up clearly through the experimental validation for the 4mm diameter catalyst channel as shown in Fig. 4(b). The gaps between experimental data and empirical correlations are reduced dramatically in case of 4mm diameter catalyst channel (ε = 0.62) analysis which is close to the application range on void fraction.

6. Conclusions

We discussed an experimental validation of a pressure drop correlations and 2D CFD analysis on a flow channel filled with catalysts in the channel. The results of the pressure drop measurements are compared with the results obtained using well-known empirical correlations and 2D CFD analysis. From the comparison results, the validity of all the correlations and 2D numerical analysis is not satisfactory. There are two kind of reasons are presumed. While the general packed channel has radially infinite and complete circular cross section, the catalyst channel has radially finite with a very narrow width (4.5mm) and irregular wavy cross section. Another reason is presumed to be because the inordinate large void fraction in the catalyst channel which is beyond the application range on void fraction in the empirical correlations.

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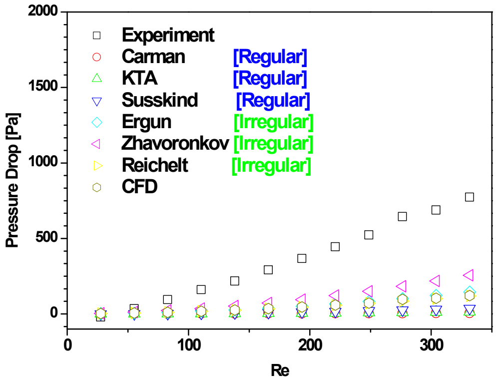
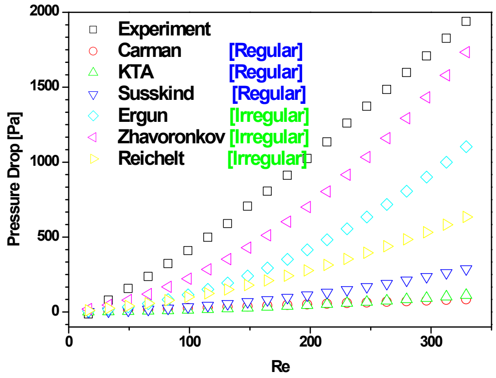


(a) 3mm diameter catalyst (ε = 0.79)



(b) 4mm diameter catalyst (ε = 0.62)

Fig. 4. Experimental validation of the empirical correlations and 2D CFD analysis

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