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Analysis of Single- and Two-phase Pressure Drop using SPACE

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1. Introduction

Passive safety system (PSS) such as passive auxiliary feedwater system (PAFS) and passive residual heat removal system (PRHRS) has been widely adopted in several advanced light water reactors (ALWRs) and small modular reactors (SMRs) [1 ~ 3].

PSS is operated by natural circulation which has relatively less driving force such as gravity, density difference, and phase change, whereas active safety system (ASS) is operated by forced circulation based on external power source such as pump. Due to the less driving force of PSS, performance of PSS is sensitive to pressure drop of system.

System analysis codes such as RELAP5, MARS-KS, and SPACE were generally used for performance evaluation of PSS. Therefore, it is important to evaluate that appropriate pressure drop model was adopted in system analysis codes.

In this study, pressure drop model adopted in SPACE 3.22 was evaluated using existing pressure drop experiments. Single- and two-phase pressure drop of straight tube were predicted using SPACE 3.22 including adiabatic and heating condition.

2. Pressure drop experiments

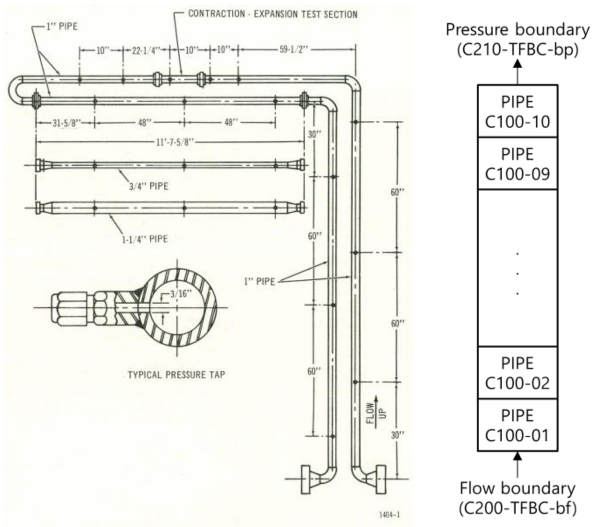
In this study, three pressure drop experiments were used for code evaluation. Description of experiments is follows.

2.1. GE-1 experiments

GE-1 experiment was conducted by General Electric Company [4] using straight tube under adiabatic, forced convection. Single- and two-phase pressure drop were measured with various flow orientation. The test section of GE-1 experiment is shown in Fig. 1(a). GE-1 experiments were conducted using circular channels (0.742, 0.954, and 1.268 in) with following test conditions.

- Pressure: 1.48 ~ 9.65 MPa
- Mass flux: 336.3 ~ 4190.8 kg/m^{2}s
- Quality: 0.0 ~ 0.9

Input model of GE-1 experiment consisted of a PIPE component (C100-PIPE) with 10 nodes for unheated test section, flow boundary (C200-TFBC-bf) for inlet and pressure boundary (C210-TFBC-bp) for outlet. Node diagram of GE-1 experiment for SPACE code analysis is shown in Fig. 1(b).



(a) (b)

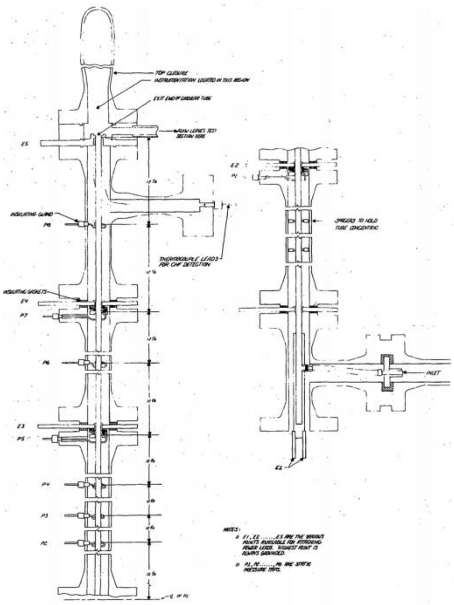
Fig. 1. Test section of GE-1 experiment: (a) schematic diagram of test section [4], (b) node diagram

2.2. GE-2 experiments

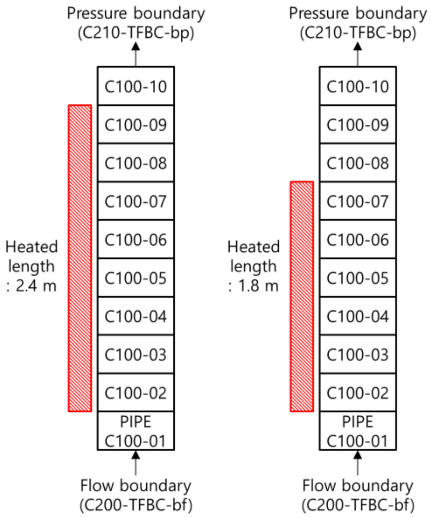
GE-2 experiment was conducted by General Electric Company [5] using straight tube under forced convection with adiabatic and heating condition. Single- and two-phase pressure drop were measured with upward flow condition. The test section of GE-2 experiment is shown in Fig. 2. GE-2 experiments were conducted using circular channels (0.68 in) with different heating length (6, 8 ft.). Followings are test conditions of GE-2 experiments.

- Pressure: 6.89 MPa
- Mass flux: 1372.5 ~ 2077.3 kg/m^{2}s
- Quality: -0.014 ~ 0.25
- Heat flux: 1750 KW/m^2

Input model of GE-2 experiment consisted of a PIPE component (C100-PIPE) with 10 nodes for unheated test section, flow boundary (C200-TFBC-bf) for inlet and pressure boundary (C210-TFBC-bp) for outlet. Node diagram of GE-2 experiment for SPACE code analysis is shown in Fig. 2(b).



(a) Schematic diagram of test section [5]



(b) Node diagram

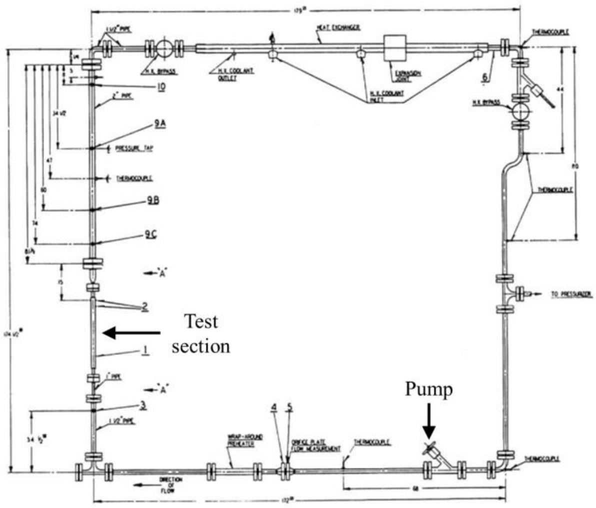
Fig. 2. Test section of GE-2 experiment

2.3. Bettis experiments

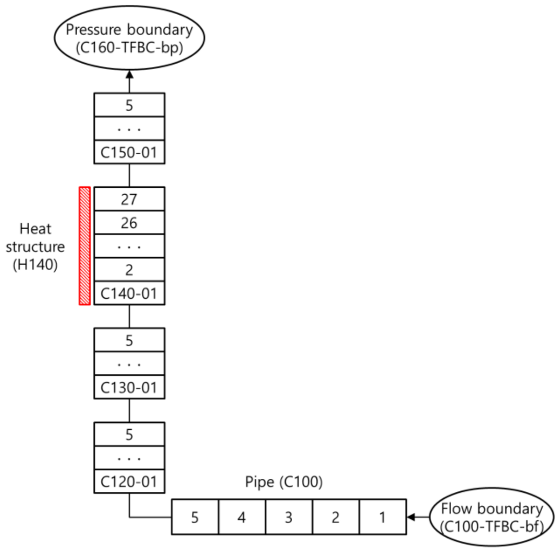
Bettis experiment was conducted by Mendler et al.[6] under forced convection with heating condition. Single- and two-phase pressure drop were measured in heated test section with upward flow condition. The test section of Bettis experiment is shown in Fig. 3(a). Bettis experiments were conducted using rectangular channel (0.2 inch spacing, 1 inch width, 27 inch long). Followings are test conditions of Bettis experiments.

- Pressure: 5.5 ~ 13.8 MPa
- Mass flow rate: 0.0642 ~ 0.0982 kg/s
- Exit quality: 0.016 ~ 0.562

Input model of Bettis experiment consisted of four PIPE components (C100, C120, C130, C150) with 5 nodes for unheated pipe and one PIPE component (C140) with 27 nodes for heated test section, flow boundary (C200-TFBC-bf) for inlet and pressure boundary (C210-TFBC-bp) for outlet. A heat structure (H140) was modeled to reflect heating condition of test section. Node diagram of Bettis experiment for SPACE code analysis is shown in Fig. 3(b).



(a) Schematic diagram of test facility [6]



(b) Node diagram of test section

Fig. 3. Test section of Bettis experiment

2.4. Pressure drop model in SPACE 3.22

In SPACE 3.22, pressure drop was calculated by Lockhart & Martinelli method [7].

$$\left(-\frac{\mathrm{dp}}{\mathrm{dx}}\right)_{2\varphi} = \varphi_g^2\left(-\frac{dp}{dx}\right)_g = \varphi_f^2\left(-\frac{dp}{dx}\right)_f \quad (1)$$

$$\mathrm{X}^2 = \frac{\varphi_g^2}{\varphi_f^2} \quad (2)$$

$$\varphi_{\mathrm{f}}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (3)$$

$$\varphi_g^2 = X^2 + CX + 1 \qquad (4)$$

In Eq. (3) & (4), Wallis model [8] and HTFS model [9] was used to calculate the coefficient C for annular flow and other flow regimes, respectively. To calculate gas-liquid interface friction, drag-coefficient model was used as basic model in SPACE 3.22. Churchill [10] correlation was used to calculate fanning friction factor in SPACE 3.22.

In this study, basic models related with pressure drop prediction in SPACE 3.22 were applied to pressure drop analysis.

3. Analysis results

3.1. Single-phase pressure drop

Analysis of single-phase pressure drop was conducted with GE-1 and GE-2 experiments. Analysis results are shown in Fig. 4. In vertical flow configuration, analysis results of pressure drop were similar with experimental results. In horizontal flow configuration, analysis results of pressure drop were slightly smaller than experimental results. In general, SPACE 3.22 well predicted single-phase pressure drop within 5 % of deviation.

3.2. Two-phase pressure drop

Analysis of two-phase pressure drop was conducted with GE-1, GE-2 and Bettis experiments.

Before the discussion of two-phase pressure drop, calculated results of exit quality were compared with measured values. Calculated exit qualities were well matched with experimental values within 1 % of error, as shown in Fig. 5.

Analysis results of GE-1 and GE-2 experiments are shown in Fig. 6(a). In vertical flow configuration, analysis results of pressure drop were smaller than experimental results. In horizontal flow configuration, analysis results of pressure drop were higher than experimental results. In general, SPACE 3.22 predicted two-phase pressure drop of circular channel within 30 % of RMS error (see Table. 1).

Fig. 6(b) shows assessment results of Bettis experiments. Generally, two-phase pressure drop in rectangular channel was under-predicted by SPACE 3.22. Deviation of two-phase pressure drop was increased with increasing flow quality. Especially, slug and annular/mist flow regime shows higher deviation of two-phase pressure drop.

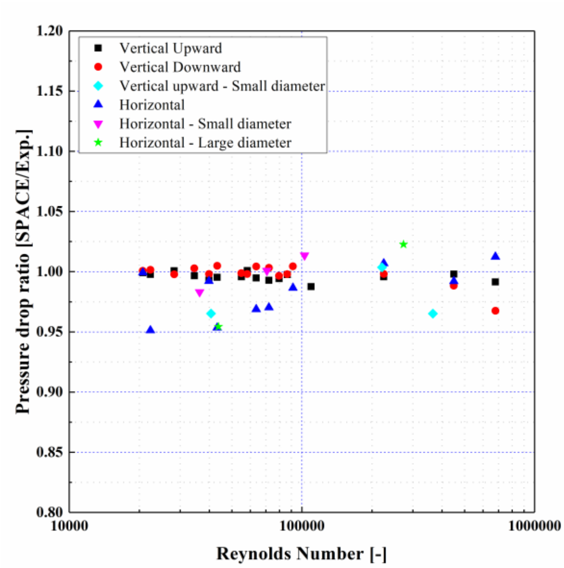


Fig. 4. Analysis results of single-phase pressure drop

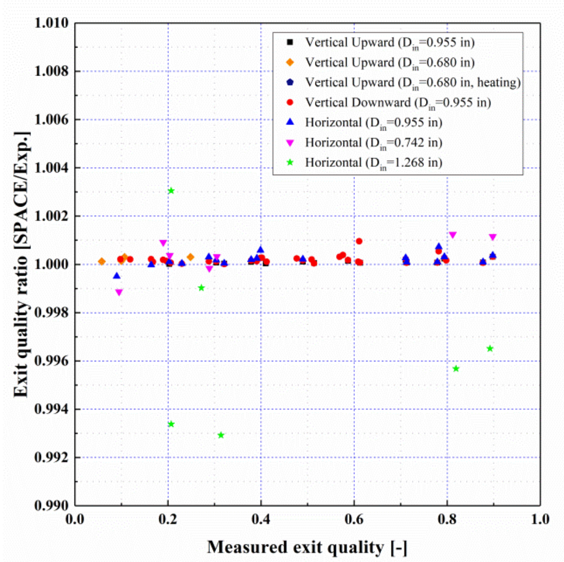
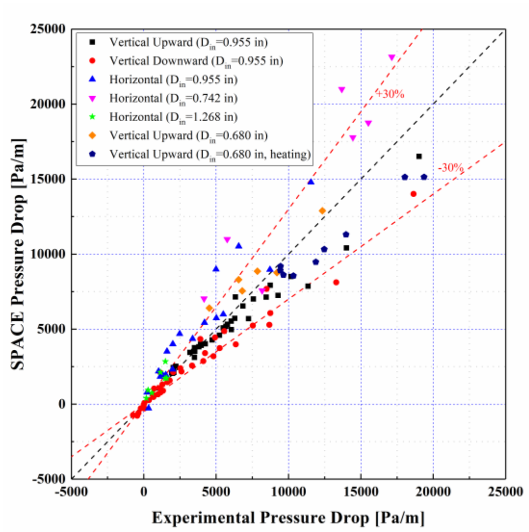


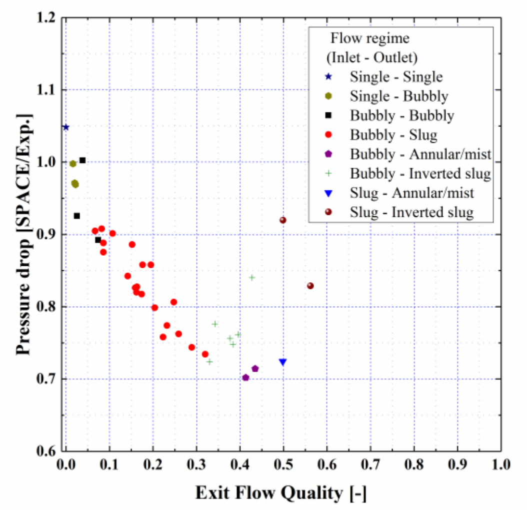
Fig. 5. Calculated exit quality of two-phase pressure drop analysis

4. Conclusions

In this study, single- and two-phase pressure drop model in SPACE 3.22 was evaluated using pressure drop experiments. For the single-phase pressure drop, analysis results were well matched with experimental results within 5 % of deviation. For the two-phase pressure drop in circular channel, SPACE 3.22 predicted pressure drop within 30 % of RMS error. For the two-phase pressure drop in rectangular channel, SPACE 3.22 under-predicted it with increasing exit flow quality. The results of this study can be helpfully used for modeling of passive safety system using SPACE 3.22.



(a) GE-1, GE-2 experiments



(b) Bettis experiments

Fig. 6. Analysis results of two-phase pressure drop

Table 1. Averaged prediction error of two-phase pressure drop.

Experiments	*RMS error (%)*
GE-1	33.6 %
GE-2	18.2 %
Bettis	18.3 %
Total RMS error	29.4 %

ACKNOWLEDGEMENT

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