Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2012

Determination of the Pipe Diameter and Length of a Sodium Experimental Installation for Single Phase Natural Convection Simulations

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1. Introduction

As a part of the verification of PDRC(Passive Decay heat Removal Circuit) concept of DSFR(Demonstration Sodium-cooled Fast Reactor)[1], KAERI will design and construct a large-scale sodium integral effect test facility called STELLA. This paper describes the selection method of the pipe of the experimental model installation, which should be designed so as to simulate various thermal-hydraulic features including the transient with natural convection heat transfer in the prototype. The scaling ratio of the model is one-fifth of the length scale, and the ratio of the temperature rise(ΔT_{oR}) through the heat exchanger is the same with the same coolant as of the prototype.

2. Method and Results

2.1 Scaling requirements

General similarity requirements for an experimental installation STELLA-2 are described in detail in Ref. 2. For the verification of the heat removal capability of the PDRC in STELLA-2, the similarity requirements of Richardson number (R) and friction number (F) should maintain unity as Eqs. (1) and (2).

$$R_R = \frac{g_R \beta_R \Delta T_{oR} l_{oR}}{u_{oR}^2} = 1 \tag{1}$$

$$F_R = \left[\sum_i \left(\frac{fl}{d} + K\right)_i \frac{1}{A_i^2}\right]_R = 1 \tag{2}$$

From Eq.(1), the ratio of Richardson number is automatically satisfied with the unity if the scaling ratio of the reference flow velocity is satisfied as $u_{oR}=(l_{oR})^{1/2}$. Thus a similarity requirement of the verification of natural convection decay heat removal represents that the scaling ratio of the distance between the heat source and heat sink satisfies the length scale (l_{oR}). Although the similarity requirement of friction number of Eq.(2) can be independently satisfied through the variation of the pipe dimension and the installation of the orifice, it is one essential point to determine the pipe dimension and the orifice size and numbers for the construction of a model facility economically and technically.

If the pipe diameters of the prototype and the model are constant, the non-dimensional area scale ratio term A_R^2 in Eq.(2) can be handled separately from the formula of summation. Generally the pipe flow resistant coefficients (K) of pipe fittings are given as constants multiplied by the pipe friction factor (f_T) [3]. If we set $K_p = b_p f_{Tp} + K_{\dot{b}}$ and $K_m = b_m f_{Tm} + K_{\dot{b}}$, Eq.(2) can be represented as

$$F_R = a_{oR}^2 \left(\frac{d_p}{d_m}\right)^4 \frac{f_m\left(\frac{l_m}{d_m}+b_m\right)+K_{\dot{b}}}{f_p\left(\frac{l_p}{d_p}+b_p\right)+K_{\dot{b}}} = 1 \tag{3}$$

Eq.(3) is the basic formula to calculate the pipe dimension of the model in the turbulent flow region. The pipe friction factor f_T in the turbulent region has the form f_T = cRe^{-n}, where Re is Reynolds number [3]. With using the mass flow rate ($\dot{m}_{oR}$) $\dot{m}_{oR} = a_{oR}(l_{oR})^{1/2}$, Eq.(3) is reduced as follows.

$$F_R = a_{oR}^2 \left(\frac{d_p}{d_m}\right)^4 \frac{\left(\frac{d_m}{d_p}\right)^n\left(\frac{l_m}{d_m}+b_m\right)+K_{\dot{b}}/f_{Tp}}{a_{oR}^n l_{oR}^{n/2}\left(\frac{l_p}{d_p}+b_p\right)+K_{\dot{b}}/f_{Tp}} = 1 \tag{4}$$

Eq.(4) is used to calculate the pipe dimension of the model for a given prototype.

2.2 Input parameters for pipe and fittings

The design pipe diameter of the PDRC pipe is 0.2488 m with a thickness 9.3mm and the length is 91.7 m. The tube side pressure drops of DHX(sodium-to-sodium decay heat exchanger) and AHX(sodium-to-air heat exchanger) of DFBR-600 are 0.57 kPa and 0.612 kPa at the sodium flow rate 31.6 kg/sec of inlet and outlet temperature 254℃ and 474℃, respectively. The schematic layout of PDRC is shown in Fig.1. The representative resistance coefficients of valves and pipe fittings are used as in Ref.4.

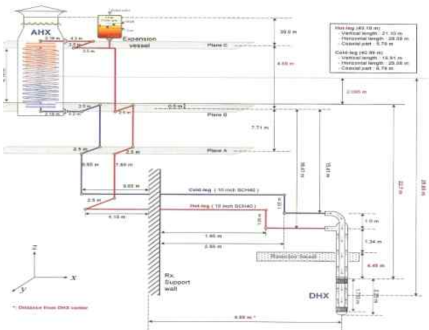

Fig. 1 Schematic pipe layout of the PDRC of DFBR-600MWe

2.3 Pipe length calculations

The vertical length of the model is determined from the similarity requirement of Richardson number. As the length scale ratio is 1/5, the vertical length becomes

5.132m, which is one fifth of the vertical height 25.66m of the prototype.

Table 1 shows the calculated pipe length of the model corresponding to the prototype pipe length of 90.17m with the arbitrary value of b_p= 1000 and 2000. For the consideration of the DHX and AHX tube side pressure drops and the pipe fittings, the total b_p of prototype system reaches 875.7 and the 3rd column shows the calculated pipe lengths. The 4th column represents the calculated results for b_p=3237.7, which can be obtained from the prototype design parameters such as geometry and flow conditions. In table 1, the negative value of pipe lengths means that the similarity requirement of F_R cannot be satisfied with a given pipe diameter. And if the calculated pipe lengths are shorter than the total length 10.26 m of the hot-leg and cold-leg, the layout of the model cannot be constructed with these pipe diameters. On the other hand, if the pipe lengths are much longer than the expected value, installing the orifices or measuring devices such as flow meters, pressure taps and thermocouples should be required in order to satisfy the similarity condition of F_R. It is desirable to select a pipe size of 2½SCH40 or 3SCH40

Table 1. Calculated pipe length of the model facility(unit: m)

Pipe size	$b_m = 1000$		$b_m = 2000$		$b_m = 875.7$		$b_m = 3237.7$	
	CR.	MA.	CR.	MA.	CR.	MA.	CR.	MA.
1½	-27.7	-28.2	-56.2	-57.1	-24.2	-24.6	-91.4	-92.9
2	15.2	3.6	10.6	-9.2	15.7	5.1	4.9	-25.1
2½	123.6	78.5	183.9	108.9	116.2	74.7	258.4	146.5
3	495.1	337.7	781.1	523.7	459.7	314.6	1135.1	754.0
3½	1180.5	755.3	1888.0	1195.9	1092.6	700.6	2763.7	1741.2
4	2309.4	1462.1	3712.1	2336.1	2135.1	1353.5	5443.7	3417.8

CR.; friction factor of Crane book[4]
MA.; friction factor correlation f_T=0.2$Re^{-0.2}$ [3]

2.4 Results and discussions

With the b_p=875.7 including the pressure losses through the heat exchanger tube-side and the pipe fittings, the calculated pipe length of the model is 116.2 m for the friction factor of Crane book[3] and 74.7m for the McAdams friction factor correlation in case of the pipe 2½SCH40. The friction factor f_T=0.2$Re^{-0.2}$ is 0.0243 instead of 0.018 of the Crane book friction factor for the simulated flow conditions. The ratio of the friction factor is 1.35 and the pipe length ratio is 1.56. The lager friction factor and the shorter pipe length are as expected. Applied friction factor correlation affects the pipe selection sensitively.

If we select the pipe 2½SCH40 using McAdams correlation, then the calculated pipe length is of 74.7 m which is too long in view of the model vertical pipe height of 5.13m. In a detailed design stage, we can layout the proper pipe length with a measuring devices. In general, we need two gate valves (K= 8f_T) for the component and loop isolation, single flow meter, several pressure taps and thermocouples. The Coriolis flow meter installed in a 2 inch pipe on STELLA-1 has a flow resistance coefficient of 12.4, which is equivalent to b_m= 510.3 or the pipe length 32.0 m of 2½SCH40. If we install the Coriolis flow meter and two gate valves in the model, the rest of the 42.7 m of calculated pipe length 74.7 m can be used for the pipe layout of the model.

3. Conclusion

For the natural convection simulations of PDRC of DFBR-600MWe in STELLA-2 (length scale of 1/5), it is reasonable to select the pipe diameter of 2½SCH40 or 3SCH40 in view of the friction number similarity requirement. For a detailed design, the types and numbers of the pipe fittings and the measuring devices have to be determined first and these values are converted to the equivalent pipe length and then the rest of required pipe length should be determined in considering the installation of orifices or a flow control valve so that the similarity of the friction number equals to unity. Since the applied friction factor correlation affects the pipe length very sensitively, much attention should be given to the flow control of the model for the acquisition of reliable data.

Nomenclature

Ψ_R *Ratio of prototype to model parameter* ($= \Psi_m/\Psi_p$)
A *non-dimensional area*
a *flow area or cross-sectional area(m²)*
b *equivalent value of l/d*
d, l *diameter or hydraulic diameter(m) & length(m)*
g *gravitational acceleration(m/sec²)*
K *resistance coefficient*
u *velocity(m/sec)*
β *thermal expansion coefficient(/℃)*

Subscripts
i *section or control volume index*
$\dot{\imath}$ *inlet and outlet index*
m *model*
o *reference*
p *prototype*
r *representative*

Acknowledgement

This study has been supported by the Nuclear Research and Development Program of the Ministry of Education, Science and Technology of Korea.

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