Steady-State Temperature Distribution along a Sodium Loop with Axial Conductivity

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Introduction

A sodium-cooled fast reactor (SFR) is a reactor that uses liquid sodium metal as a coolant. This coolant has higher thermal conductivity than the water in conventional light water reactors. The Peclet number is generally large and can be neglected in the coolant energy equation. Its effect, however, cannot arbitrarily be neglected for sodium under low-flow conditions. It is therefore necessary to examine the Peclet number. In the case of the STELLA-2 sodium loop experimental apparatus, the natural convection driving force would be reduced to 1/5, but the influence of the axial heat conduction is increased five times as the scale in the longitudinal direction is reduced to 1/5. Therefore, in order to realize the same physical phenomenon in the simulation experiment, it is necessary to assure that the thermal conduction phenomenon is reflected in the scaling or that it has negligible effect on the behavior of the entire system.

Equations

The circuit consists of two horizontal pipes and two vertical pipes. It originates from the beginning of the lower heated section, and it cools down in the upper section. The analysis is based on a one-dimensional approach. The space coordinate s runs around the loop. Fig.1 shows a schematic diagram of the loop used for analysis. One-dimensional single-phase energy equations with axial conductive heat transfer with rectangular closed loop geometry and incompressible flow are given as:

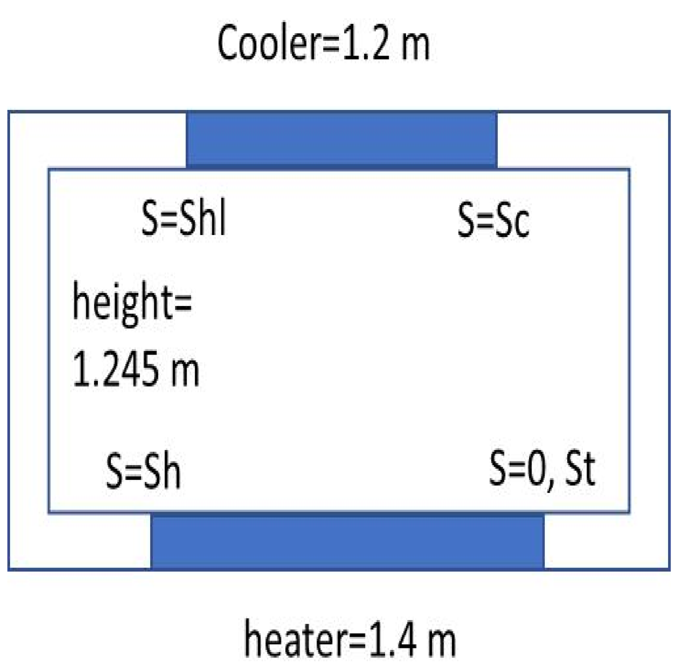

Fig.1. Schematic diagram of the closed loop.

Table 1: Parameter of loop.

Parameter	
Loop height [m]	1.245
Loop width [m]	1.48
Inner diameter [m]	0.04
Heater length [m]	1.4
Cooler length [m]	1.2

Heater: $$\rho_0 C_p\left(\frac{\partial T}{\partial t}+\frac{W}{A\rho_0}\frac{\partial T}{\partial s}\right)=\frac{4q}{D}+\frac{1}{A}\frac{\partial}{\partial s}\left(kA\frac{\partial T}{\partial s}\right)$$

Cooler: $$\rho_0 C_p\left(\frac{\partial T}{\partial t}+\frac{W}{A\rho_0}\frac{\partial T}{\partial s}\right)=-\frac{4U_i(T-T_s)}{D}+\frac{1}{A}\frac{\partial}{\partial s}\left(kA\frac{\partial T}{\partial s}\right)$$

Pipes: $$\rho_0 C_p\left(\frac{\partial T}{\partial t}+\frac{W}{A\rho_0}\frac{\partial T}{\partial s}\right)=\frac{1}{A}\frac{\partial}{\partial s}\left(kA\frac{\partial T}{\partial s}\right)$$

The equations are non-dimensionalized by using the following dimensionless governing parameters.

$$S=\frac{s}{H},\ \omega=\frac{W}{W_{ss}},\ \tau=\frac{tW_{ss}}{V\rho_0},\ \theta=\frac{T-T_s}{(\Delta T_h)_{ss}}$$

The equations would be:

Heater: $$\frac{\partial\theta}{\partial\tau}+\frac{L_t}{H}\omega\frac{\partial\theta}{\partial S}=\frac{L_t}{L_h}+\frac{1}{Pe^*}\frac{\partial^2\theta}{\partial S^2}$$

Cooler: $$\frac{\partial\theta}{\partial\tau}+\frac{L_t}{H}\omega\frac{\partial\theta}{\partial S}=-St_m\theta+\frac{1}{Pe^*}\frac{\partial^2\theta}{\partial S^2}$$

Pipes: $$\frac{\partial\theta}{\partial\tau}+\frac{L_t}{H}\omega\frac{\partial\theta}{\partial S}=\frac{1}{Pe}\frac{L_tD}{H^2}\frac{\partial^2\theta}{\partial S^2}=\frac{1}{Pe^*}\frac{\partial^2\theta}{\partial S^2}$$

The non-dimensional groups are expressed as:

$$Re=\frac{WD}{\mu A},\ Pr=\frac{\mu C_p}{k},\ Nu=\frac{U_iL_t}{k},\ St=\frac{U_iA}{WC_p},\ St_m=\frac{4Nu}{Re_{ss}Pr}$$

Dimensionless mass flow rate, ω=1 in the steady-state condition and H=height of pipe, L_t=total length of loop. By applying the temperature conditions: θ3=heater inlet, θ4=heater outlet, θ1=cooler inlet, θ2=cooler outlet.

The analytical solutions of temperature distribution in the steady-state condition along the loop are expressed as:

Heater: $$\theta=\left[\theta 3-\frac{\theta 4-\theta 3-\frac{H}{L_h}S_h}{e^{\left(\frac{L_t}{H}Pe^*\right)S_h}-1}\right]+\left[\frac{\theta 4-\theta 3-\frac{H}{L_h}S_h}{e^{\left(\frac{L_t}{H}Pe^*\right)S_h}-1}\right]e^{\left(\frac{L_t}{H}Pe^*\right)S}+\frac{H}{L_h}S$$

Hot Pipe:
$$\theta=\left[\theta 1-\frac{\theta 1-\theta 4}{e^{\left(\frac{L_t}{H}Pe^*\right)S_{hl}}-e^{\left(\frac{L_t}{H}Pe^*\right)S_h}}e^{\left(\frac{L_t}{H}Pe^*\right)S_{hl}}\right]+\left[\frac{\theta 1-\theta 4}{e^{\left(\frac{L_t}{H}Pe^*\right)S_{hl}}-e^{\left(\frac{L_t}{H}Pe^*\right)S_h}}\right]e^{\left(\frac{L_t}{H}Pe^*\right)S}$$

Cooler:
$$\theta=\left[\theta 2\, e^{(-m1)S_c}-\frac{\theta 1\, e^{(-m1)S_{hl}}-\theta 2\, e^{(-m1)S_c}}{e^{(m2-m1)S_{hl}}-e^{(m2-m1)S_c}}e^{(m2-m1)S_c}\right]e^{(m1)S}+\left[\frac{\theta 1\, e^{(-m1)S_{hl}}-\theta 2\, e^{(-m1)S_c}}{e^{(m2-m1)S_{hl}}-e^{(m2-m1)S_c}}\right]e^{(m2)S}$$

Cold Pipe:
$$\theta=\left[\theta 3-\frac{\theta 3-\theta 2}{e^{\left(\frac{L_t}{H}Pe^*\right)S_t}-e^{\left(\frac{L_t}{H}Pe^*\right)S_c}}e^{\left(\frac{L_t}{H}Pe^*\right)S_t}\right]+\left[\frac{\theta 3-\theta 2}{e^{\left(\frac{L_t}{H}Pe^*\right)S_t}-e^{\left(\frac{L_t}{H}Pe^*\right)S_c}}\right]e^{\left(\frac{L_t}{H}Pe^*\right)S}$$

Where,
$$\mathrm{m1,m2}=\frac{\frac{L_t}{H}Pe^*\pm\sqrt{\left(\frac{L_t}{H}Pe^*\right)^2+4St_mPe^*}}{2}$$

Because the temperature slopes are the same at the outlet and inlet of the heater and cooler, four equations can be derived. From these four equations, four unknown temperatures: θ4, θ1, θ2, and θ3 can be solved. The Newton-Raphson method was used to solve them. Fig. 2 shows the temperature distribution along the loop for different values of the Peclet number. Fig. 3 and Fig. 4 show the temperature distribution for different values of the height and diameter. Fig. 5 shows the temperature distribution at different scales. From the figure, it can be seen that two temperature distributions at Pe = 0.1 are coincident with each other when the height and diameter are scaled down at the same rate.

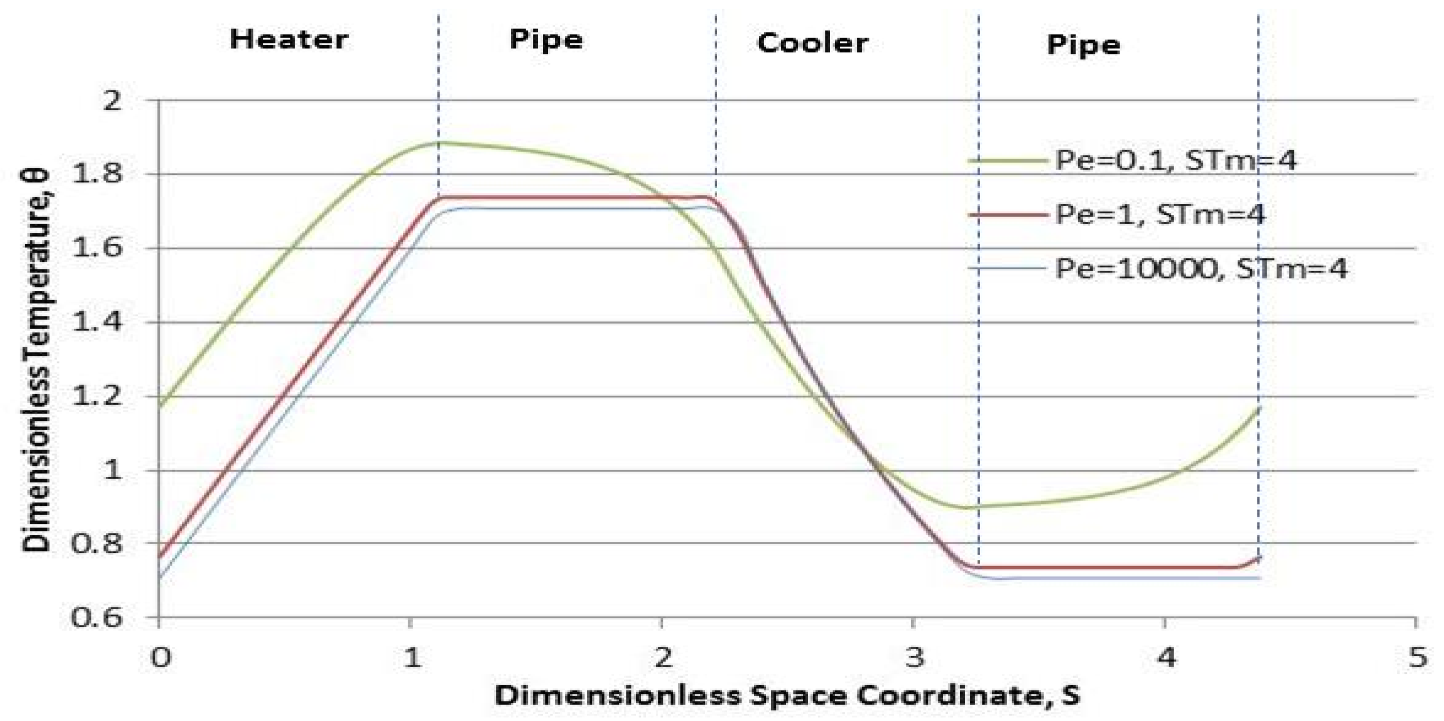

Fig. 2. Steady-state temperature distribution along the loop for different values of the Peclet number.

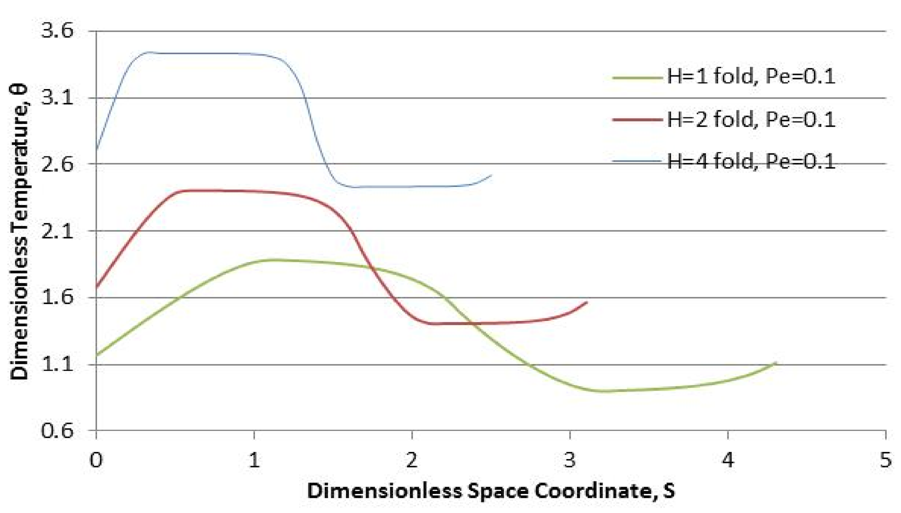

Fig. 3. Steady-state temperature distribution along the loop for different values of the height.

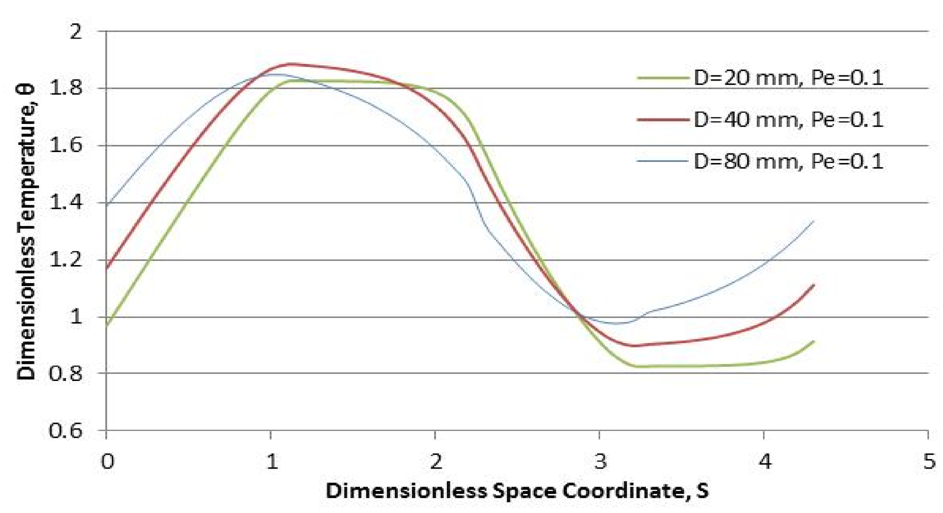

Fig. 4. Steady-state temperature distribution along the loop for different values of the diameter.

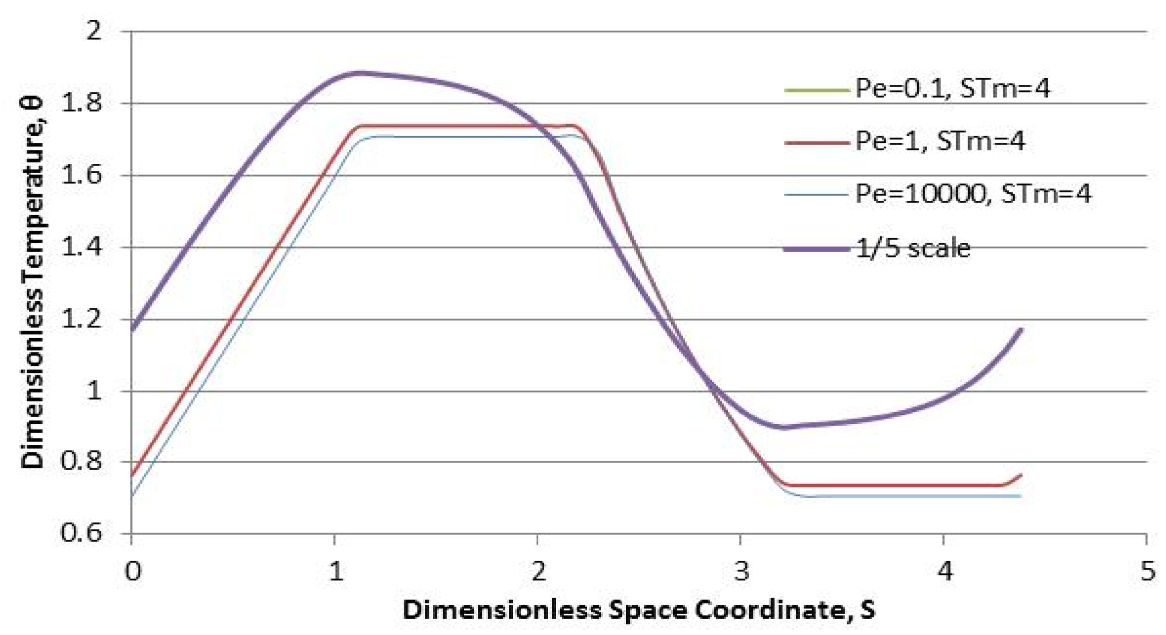

Fig. 5. Steady-state temperature distribution along the loop for different scales at Pe = 0.1.

Conclusions

- **Exact solutions to a rectangular sodium loop with the axial heat conduction have been developed. When the height and diameter of the loop are scaled down at the same rate, the temperature distributions for different scale are coincident with each other.**

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