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Influence of Diameter and Cross-Section of a Chimney on the Heat Transfer: Simplified Balance Equation Approach

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1. Introduction

The need for the implementation of the passive safety characteristics for the NGNP (Next Generation Nuclear Plant) has grown. A chimney can be used as an important heat sink of a nuclear system because it provides effective and stable means of heat removal.

Within a chimney, a buoyant head is established as the air is heated, expands, rises, and exits the stack with cold air drawn in at the chimney inlet (Fig. 1). And the convective heat transfer and friction pressure drop processes inside the chimney depend on the velocity profile at the wall.

The objective of the present work is to investigate the influence on the varied diameter and different cross-sectional shape of a chimney on the heat transfer using simplified balance equation approach.

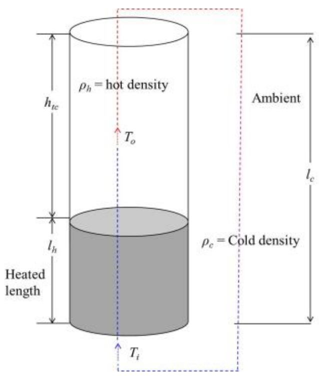

Fig. 1. Schematic of a chimney natural convection circuit.

2. Theoretical background and proceeding

2.1 Momentum and Fluid-Energy Conservation

The heat removal capability of a chimney is derived by the simultaneous solution of the one-dimensional momentum equation for the air circuit and the fluid-energy equation for the heated section [1].

$$\rho_c \beta g h_{tc} \Delta T = \left(2\frac{f}{D_h}\frac{l_c}{\bar{\rho}} + \frac{1}{\rho_c}\left(\frac{\beta\Delta T}{1-\beta\Delta T}\right) + \frac{1}{2}\left(\frac{K_i}{\rho_c} + \frac{K_o}{\rho_h} + \frac{K_{orf}}{\bar{\rho}}\right)\right)\rho^2\upsilon^2 \qquad (1)$$

$$\dot{m}C_p\left(T_i - T_o\right) = hA_h\left(T_s - T_\infty\right) \qquad (2)$$

Where ρ is density, β is volume expansion coefficient, g is gravitational acceleration, h_{tc} is exit length, ΔT is the heated section temperature rise, G is mass flux, f is friction factor, l_c is overall length of system, D_h is hydraulic diameter which is equal to four times the flow area divided by the wetted perimeter, K is loss factor, $\dot{m}$ is mass flow rate, C_p is heat capacity, T is temperature, h is heat transfer coefficient, and A_h is the cross-sectional area of the heated section, and the subscripts *c*, *h*, *i*, *o*, *s*, and *orf* represent the cold, hot, inlet, outlet, surface, and orifice, respectively.

2.2 Iterative method

In order to get the simultaneous solution using the balance equations, an iterative method was devised to get the velocity of fluid and Nu_D in the chimney.

Assuming and using a potential flow velocity from the equation (1), the initial Re_D was determined.

To derive the heat transfer coefficient, the heat transfer correlation of Sieder and Tate [2] was used, which were derived for the combined developing entry length.

$$Nu_D = 1.86\left(\frac{\mathrm{Re}_D\,\mathrm{Pr}}{L/D}\right)^{1/3} \qquad (3)$$

Using equation (2), the temperature difference between chimney inlet and outlet was calculated, which determines the magnitude of buoyant head that drives the fluid in the chimney system.

Using the temperature difference, next velocity can be calculated by the equation (4), which is basically the same with the equation (1).

$$\upsilon = \sqrt{\frac{\rho_c g h_{tc} \beta\Delta T}{\left(2\frac{f}{D_h}\frac{l_c}{\bar{\rho}} + \frac{1}{\rho_c}\left(\frac{\beta\Delta T}{1-\beta\Delta T}\right) + \frac{1}{2}\left(\frac{K_i}{\rho_i} + \frac{K_o}{\rho_o} + \frac{K_{orf}}{\rho}\right)\right)\rho^2}} \qquad (4)$$

The iterative calculation using the equations (3) and (4) were performed until the velocity and the Nusselt number were unchanged.

3. Results and discussion

3.1 Comparison with experiments

The calculated Nu_D's using the simplified balance equations were compared with the experiments of Lim and Chung [3]. They carried out the natural convection heat transfer experiments of a chimney of Ra_D 7.23$\times10^9$ for various exit lengths using the analogy concept. As shown in Fig. 2, the two Nu_D's show good agreement. The maximum and minimum errors were 5.44% and 1.35%, respectively. As the exit length increases, the heat transfer enhances, but up to a certain length. Further extension of the exit length does not vary the heat transfer.

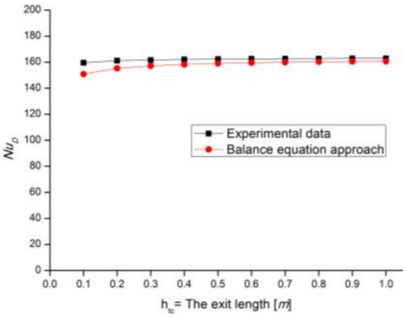

Fig. 2. Comparison between the experimental and theoretical Nu_D for the exit length.

3.2 Determination of the effective length

The gravity and the friction heads increase with the exit length increase. The rates of the gravity and the friction head increases are different but they become equal after a certain length, which means that the improved buoyance is used to overcome the friction.

Figure 3 present the growth ratios of the gravity and the friction heads at each exit length and the effective exit length.

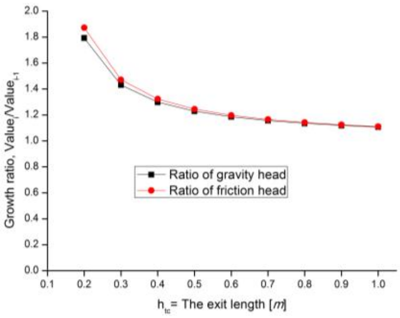

Fig. 3. The growth ratio, $gravity_i/gravity_{i-1}$ and $friction_i/friction_{i-1}$, as exit length.

3.3 The effect of varied diameter of chimney

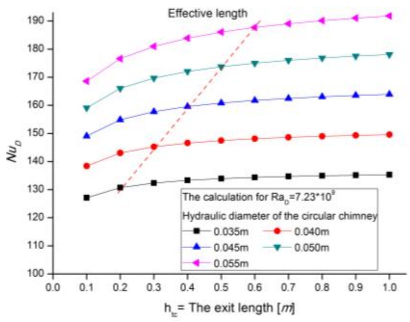

Fig. 4. The effects of varied diameter of chimney.

Figure 4 shows the calculated Nu_D for the 0.035*m*, 0.04*m*, 0.045*m*, 0.05*m* and 0.055*m* hydraulic diameters of circular chimneys. The heat transfer rates increases and the effective length becomes longer due to reduced friction as the hydraulic diameter of the chimney increases.

3.4 Effect of cross-sectional shape of a chimney

Figure 5 presents the effects of cross-sectional shape of a chimney. The Nu_D in the equilateral triangle chimney with increasing the exit length is the largest of chimneys and the Nu_D in the square chimney is larger than those in the circular chimney. Because the friction is reduced since the area of equilateral triangle chimney which is out of the fluid is the actually biggest among all chimneys.

However, the point of the effective length is same as 0.7*m* in the every case. It seems to be equal as the hydraulic diameter of all chimneys is same.

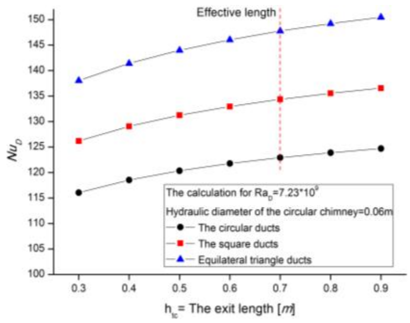

Fig. 5. Effects of different cross-sectional shape of a chimney.

4. Conclusions

A simplified balance equation approach was devised and it predicts the experiments reasonably.

The influence of the varied diameter and different cross-sectional shape of a chimney on heat transfer was investigated theoretically.

The effective length depending on hydraulic diameter is caused due to the balance between gravity and friction. The gravity and the friction heads increase with the exit length increase. The friction head decreases with the hydraulic diameter increase.

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