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# AN EXPERIMENTAL INVESTIGATION OF NATURAL CIRCULATED AIR FLOW IN THE PASSIVE CONTAINMENT COOLING SYSTEM

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## ABSTRACT

The objective of this study is to investigate the effects of air inlet position and external conditions on the natural circulated air flow rate in a passive containment cooling system of the advanced passive reactor. Experiments have been performed with 1/36 scaled segment type passive containment test facility. The air velocities and temperatures are measured through the air flow path. Also, the experimental results are compared with numerical calculations and show good agreement.

## INTRODUCTION

Since TMI and Chernobyl accidents, a significant increase of safety in future nuclear plants has been demanded. Thus, suggested alternative is passive reactors, which adopt passive safety features operated by gravity or natural circulation at accidents. Those system should be simple, reliable and minimize the operator action. AP600 is one of such reactors developed by Westinghouse. In AP600[1], several passive safety systems are to be installed including the passive containment cooling system as ultimate heat sink to prevent the containment shell from exceeding its design pressure. The system uses natural air circulation between the steel shell containment and the concrete shield building, whose cooling is enhanced by draining water onto the steel shell. In order to verify the effectiveness of this system and provide the data for detailed design, many experiments and analytical works have been performed or still ongoing for the heat transfer, air flow, water distribution and so on[2,3].

AP600 has the air inlet at the top of shielding building to exclude the effect of surrounding buildings on the inlet air flow, instead of the bottom inlet in Ebasco's NPR-HWRF containment system and B&W ASPWR[4] which has more benefit in the air natural circulation. Westinghouse has performed the wind tunnel test to determine the optimum location for PCCS air inlet, the effect of wind direction blowed at the chimney and the air flow path resistance test and so on[5]. Consequently, The air flow was insensitive to the wind direction, and total cooling path of reduced loss coefficient resulted in an increased air flow for a given heated air buoyancy force.

The purpose of this study is to examine the propriety of top air inlet in AP600 and to provide the data for analytical tools which estimate the coolability of PCCS. Thus, the effects of air inlet position and external conditions on natural circulated air flow rate were investigated with 1/36 length scaled AP600 containment. The test facility is composed of steel containment including heaters, up and downward air paths and blower and so on. This geometry is scaled by a scaling factor which is derived by two-dimensional governing equations. The scaling factor, $Gr/Re^2$ is chosen because this factor is dominant in the natural circulation phenomena and other nondimension number such as Pr and Ec have relatively small effect in governing equations for this experiment using the air. The steel containment and air path geometrical dimensions are 103 cm height and 50 cm width with the same shape as AP600. The gap sizes of inner and outer air path are 1.5 and 5 cm, respectively. The containment is filled with the hot water. The natural circulated air flow velocity is measured at the inner air path with hot-wire anemometer. The experiments have been performed varying the size of air inlet, air inlet temperature, external wind velocity and air inlet position. And, the effect of outlet steam toward the air inlet due to the external wind has been tested.

To compare with experimental results, numerical calculations are performed with a one-dimensional steady air natural circulation model. The results show good agreement.

EXPERIMENT FACILITY AND MEASUREMENT

The configuration of experiment facility is shown in Figure 1, which includes air path, chimney, steel containment, electric heater, blower and so on. The dimensions of steel containment and air path, which have the same shape as AP600, are 103 cm height and 50 cm width. The gap sizes of inner and outer air path are 1.5 and 5 cm, respectively. Air path and chimney are made of acryl plates. This configuation correspond to 1/36 length scaled AP600 containment and is designed by the scaling factor, $Gr/Re^2$, which is derived from two-dimensional governing equations[6].

To maintain the wall surface temperature, the containment is filled with the hot water which is heated by two 3 kw heaters installed inside. And at the top, the blower is installed at the opposite position of air inlet and blows the air to investigate the effect of external wind on the top of chimney. And, to prevent the heat loss from containment to atmosphere, the sides are insulated by ceramic fiber.

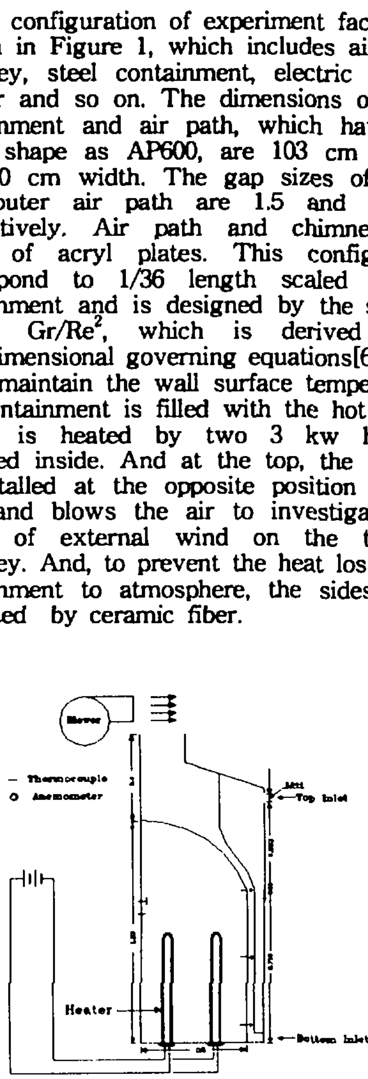


Fig. 1 Configuration of Experimental Facility

Measurements are implemented for the air velocity through inner air path and the wall temperature by the hot wire anemometer located at center of path and stainless steel sheathed thermocouple which is welded by using of the soldering paste. In this study, the smoke wire[7] is also used for cross-checking because the reliability of hot-wire detection is known to be questionable for such a low velocity near 1 m/s in the present experiments. However, quantitative comparisons are failed due to the turbulent dispersion for low velocity and difficulty of high-speed photographing.

During experiments, the wall temperature is controlled to maintain constant and recorded. Finally, ambient, inlet and exit temperatures are measured. And, the external wind velocities for various experiment conditions are measured.

EXPERIMENTAL RESULTS

Experiments are performed varying height (top vs bottom) and width (300x40 mm vs 210x14 mm) of air inlet, air inlet temperature (14.0 - 20.6 ℃) and veolcity (1.20 ~ 3.45 m/s) of external wind. The results are shown in Figure 2 to 4. As shown in Figure 2, even though the range of ambient temperature is narrow due to the difficulty of generating such experimental conditions, the trend is obvious that the air velocity decreases as the inlet air temperature increases. However, for the bottom air inlet, the influence is much smaller. And, Figure 3 shows that the increase of external wind velocity increases the air velocity due to the suction effect. From this result, the inlet air temperature is a dominant parameter affecting the natural circulated air flow rate and thus, the effect of outlet steam toward the air inlet due to the external wind seems small because the air velocity continues to be increased as the wind velocity increases. Also, we tested the effect of the inlet geometry by reducing the area of inlet. Figure 4 shows that the inlet restriction increases the air velocity in the inner baffle gap. Finally, Table 1 shows the air velocities for the top and bottom inlets

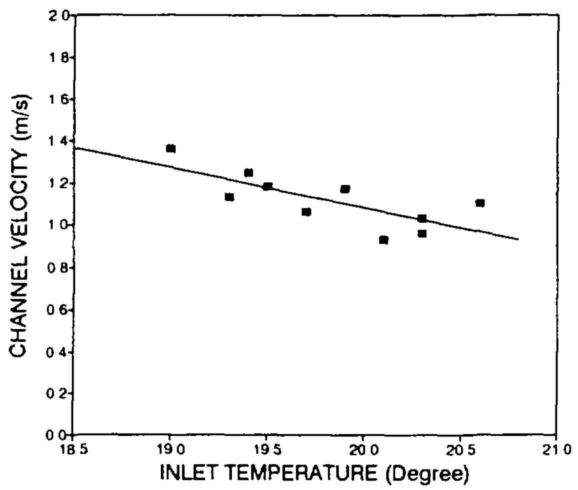


Fig. 2 Air Channel Velocity to Ambient Temperature (Top Inlet)

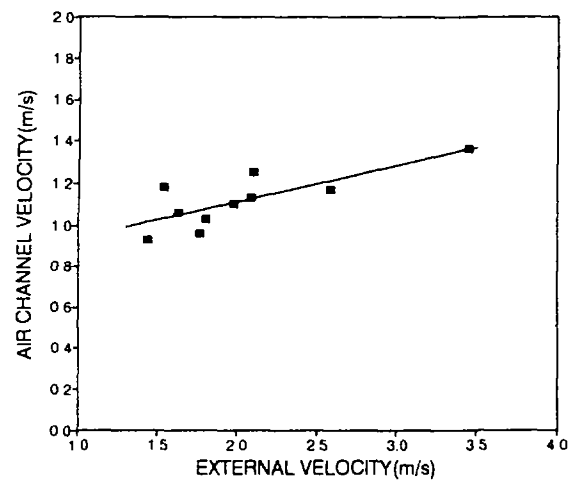


Fig. 3 Air Channel Velocity to External Wind Velocity (Top Inlet)

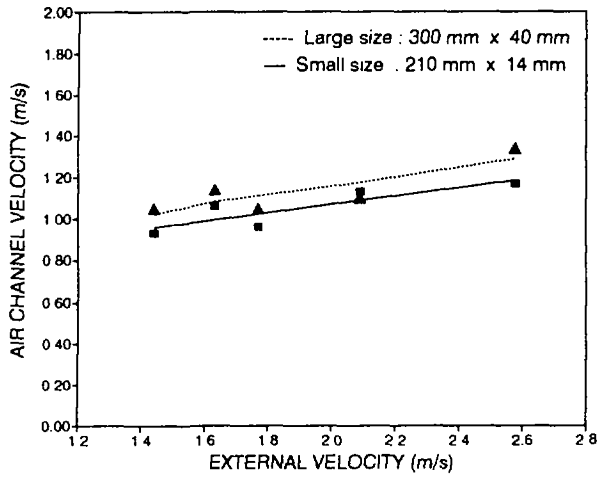


Fig. 4 Air Channel Velocity for Different Air Inlet Size (Top Inlet)

when the air of different temperature (low at the top and high at the bottom) enters. In this result, the bottom position good for the natural circulation will lose its benefit if the surrounding building block the air flow and increase the ambient temperature.

## NUMERICAL CALCULATION

In this study, in order to be compared with experimental results, numerical calculations are performed with a one- dimensional steady air natural circulation model. For the sake of simplification, the constant wall temperature and insulated conditions are assumed. In steady state, mass flow rate of air flowing along the air path is not changed. In heating region, the air density is no more constant and thus assumed to be a function of air temperature. The air temperature variation in this region is calculated from the heat ballance equation given as,

$$m\,C_p\,(T_i - T_{i-1}) = h\,(T_w - T_M)\,\Delta A_i \qquad (1)$$

In equation (1), the heat transfer coefficient used in this study is Hugot's experimental data[8]which is a function of gap size and temperature difference. In such a closed control volume as this geometry, this correlation is concluded to be the most suitable. Then, since $T_M = \frac{T_i + T_{i-1}}{2}$, the inlet temperature of subsequent node can be obtained from equation (1) as,

$$T_i = \frac{\left(m\,C_p - \frac{h\,\Delta A_i}{2}\right) T_{i-1} + h\,T_w\,\Delta A_i}{m\,C_p + \frac{h\,\Delta T_w}{2}} \qquad (2)$$

Now, the density variation at each heated node is calculated from equation of state since the air density is a function of temperature.

We can calculate the air velocity in the natural condition where the total pressure drop and the total buoyancy driven force should be equal. In this calculation, the pressure drops from friction loss and local loss are obtained as follows,

$$\Delta P = K\,\frac{1}{2}\,\rho\,v^2 \qquad (3)$$

In this equation, the loss coefficient for each node is calculated from Ref.[9]. The buoyancy driven force can be calculated from the following equation,

$$f = \sum_i (\rho_a - \rho_i)\,g\,\Delta Z_i \qquad (4)$$

Finally, calculations are repeated by modifying the initial air velocity until satisfying the steady natural circulation conditions. The nodalization scheme is shown in Figure 5. The tables 1 and 2 show the calculated results for various conditions. As shown in the tables, the calculations quite well predicted the experimental results for higher external velocity. However, for low velocity, some discrepancies exist. This seems to be caused from the uncertainties of measurement for the low velocity. The result of Case 8 shows the reversal trend compared with other cases as shown in Table 1. This is due to the direct differential pressure increase in this simple model as the wind velocity increases and some degree of uncertainties.

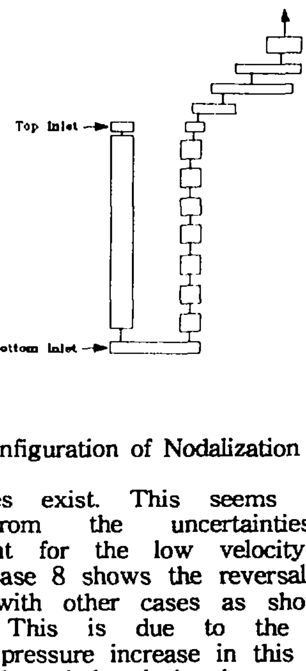


Fig. 5 Configuration of Nodalization

## DISCUSSION AND CONCLUSIONS

In this study, experiments with 1/36 scaled segment-type test facility have been performed to investigate effects of air inlet position and external conditions on the natural circulated air flow rate in the PCCS of AP600.

The experimental results show that the air velocity increases as the inlet air temperature decreases and the external wind velocity increases. Also, the reduction of air inlet area decreases the natural circulated air flow. Finally, it concluded that the bottom position will lose its benefit if the surrounding buildings block the air flow or increase the ambient temperature.

Also, a simple one-dimensional steady air flow model developed in this study shows good agreement.

Table 1 Comparison Air Velocity for Top and Bottom Inlet

| CASE | INLET POSITION | AMB.TEMP. Deg. C | WALL TEMP. Deg. C | WIND VELOCITY m/s | AIR VELOCITY m/s | |
|---|---|---|---|---|---|---|
| | | | | | EXP. | CALC. |
| 1 | TOP | 13.3 | 96.4 | 1.45 | 1.05 | 0.89 |
| 2 | BOTTOM | 18.0 | 93.9 | 1.39 | 0.92 | 0.83 |
| 3 | TOP | 16.4 | 96.6 | 1.84 | 1.05 | 1.00 |
| 4 | BOTTOM | 19.4 | 94.8 | 1.77 | 0.98 | 0.96 |
| 5 | TOP | 17.7 | 97.6 | 2.07 | 1.10 | 1.16 |
| 6 | BOTTOM | 19.8 | 96.7 | 2.12 | 1.08 | 1.09 |
| 7 | TOP | 17.7 | 97.9 | 2.51 | 1.34 | 1.33 |
| 8 | BOTTOM | 19.4 | 95.2 | 2.82 | 1.09 | 1.45 |

Table 2 Comparison of Calculated Results to Experimental Data

| CASE | CONDITION | AMB. TEMP. Deg. C | WALL TEMP. Deg. C | WIND VELOCITY m/s | AIR VELOCITY m/s | |
|---|---|---|---|---|---|---|
| | | | | | EXP. | CALC. |
| 1 | LARGE TOP | 13.3 | 96.4 | 1.45 | 1.05 | 0.89 |
| 2 | LARGE TOP | 15.4 | 96.9 | 1.69 | 1.14 | 0.86 |
| 3 | LARGE TOP | 16.3 | 97.1 | 1.77 | 1.16 | 0.98 |
| 4 | LARGE TOP | 17.7 | 97.6 | 2.07 | 1.10 | 1.16 |
| 5 | LARGE TOP | 17.7 | 97.9 | 2.51 | 1.34 | 1.33 |
| 6 | SMALL TOP | 20.1 | 97.8 | 1.44 | 0.93 | 0.77 |
| 7 | SMALL TOP | 19.7 | 98.2 | 1.63 | 1.06 | 0.81 |
| 8 | SMALL TOP | 20.3 | 98.0 | 1.81 | 1.03 | 0.86 |
| 9 | SMALL TOP | 19.3 | 97.6 | 2.09 | 1.13 | 0.95 |
| 10 | SMALL TOP | 19.9 | 98.9 | 2.58 | 1.17 | 1.18 |

NOMENCLATURE

$C_p$ Specific heat at constant pressure of air
$h$ Heat transfer coefficient
$K$ Loss coefficient
$\dot{m}$ Mass flow rate of Air
$T_{bi}$ Bulk temperature of node i
$T_i$ Outlet temperature of node i
$T_{i-1}$ Inlet temperature of node i
$T_w$ Heating wall temperature
$\Delta A_i$ Heat transfer area of node i

$\Delta Z_i$ Height of node i

$\rho_a$ Ambient air density

$\rho_i$ Air density of node i

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