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An effect of a horizontal buoyant jet on the temperature distribution inside a hot water storage tank

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ABSTRACT

The hot water storage tank (for stratified thermal storage) with a heat pump draws a lot of attention nowadays due to its high performance. In Japan, reheating of the bath is commonly used, and as this mode, the jet injects horizontally at the middle of the tank, so the temperature distribution of the tank changes complexly with time. Hence a model is needed to simulate this phenomenon, precisely. Additionally, in the process of designing a hot water storage system, it is necessary to simulate temperature distribution quickly, since a test run itself is a time consuming process.

In this study, visualization experiments were performed using tracer particles and thermo-sensitive liquid crystals. Experiments were also carried out to find the unsteady temperature distribution in a tank when the positively or negatively buoyant jet was injected horizontally in the middle of the tank whose size is limited and has an influence from the opposite wall.

If the momentum effect of the buoyant jet is stronger than that of buoyancy, the buoyant jet impinge against the opposite wall of the tank, and a vortex was observed near the opposite wall. Empirical formulas were proposed to predict the height of the vortex "Z_b" under various conditions, such as the momentum and the buoyancy of the buoyant jet, and the Prandtl number of the tank water. Furthermore, the 3D-CFD was carried out to supplement the 3D behavior of the inner tank fluid.

A one dimensional model, "uniformly distributed injection model", for simulating temperature distribution was proposed. The performance of the model was verified by comparing the results with the unsteady temperature distribution obtained experimentally. The model was also compared with the measurements obtained using a commercially available hot water storage system. Both results showed good agreements. Hence adequacy of the model was clarified.

1. Introduction

In Japan, CO_2 heat pump water heaters (a hot water storage system with a heat pump using CO_2 as refrigerant) for residential use have become widespread (Saikawa et al., 2001). For standard households (4 family members), the heat pump water heater consists of the tank of 370 L and the heat pump of 4.5 kW (rated output). The "heating water by heat pump mode" operates mainly from midnight till morning. In this mode, the water is withdrawn from the bottom of the tank, heated by the heat pump up to 65–90 °C, and returned to the top of the tank, where it is stored as stratified in a thermal storage tank. The tank will be of full capacity in terms of heat storage by the next morning. And from the morning till the night, the hot water is used for hot water supply for taps, showers, filling the bath, or it is used for a heat source to reheat the bath. In Japan, the following pattern of using hot water (e.g. the test mode of JIS C9220 (2011)) is common, which is filling the bath to about 180 L, and keeping it at a hot temperature for about 3 h (automatic heat-retention). In "automatic heat-retention", the hot water in the tank is used for a heat source to reheat the bath water through the heat exchange.

The heat pump is used as the heat source of the heat pump water heaters. The heat pump COP (Coefficient of Performance) is influenced by the time-history of the inlet water temperature to the gas cooler (the CO_2–water heat exchanger in the heat pump). Therefore, the heat pump COP strongly influences the system performance of the heat pump water heaters. The water at the bottom of the tank flows into the gas cooler of the heat pump, so the prediction of the temperature distribution of the tank is important. For the demand of cyclostationarity in the testing of the system performance, several days or more is needed for the test by applying the load sequentially. The sequential load amounts depend on hot water supply and bath heating demand. To promote the development of the estimation efficiently, a high-speed 1-dimensional simulation model (1D model) for predicting the temperature

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distribution of the tank is necessary (Toyoshima et al., 2008). And, with reheating bath mode, the jet injects water horizontally at the middle of the tank, so the temperature distribution of the tank changes complexly with time. Hence the model is needed to simulate this phenomenon, precisely.

As the buoyant jet under the influence of the positive or negative buoyancy, the trajectory of the jet changes due to the influence of the momentum of the jet and the passive buoyancy from the tank water (Fischer et al., 1979). To simulate the thermal diffusion phenomenon of the inner tank by using the 1D model, a special method is needed to consider the influence of the buoyant jet and the turbulence. According to the past studies, the following models are proposed. If the temperature of the lower node is higher than the higher node (temperature inversion), then the temperature of the nodes involved in the inversion are interchanged, "Multinode with inversion" (Franke, 1997). A weighted mean temperature is applied between the two nodes involved in the temperature inversion, "Multinode with mean" (Kleinbach et al., 1993). In the case of injecting from the top or the bottom of the tank, the thermal diffusivity and the shape of the baffle plate are considered by using the empirical effective diffusivity factor to have the effect of magnification (Zurigat et al., 1988; Al-Najem and El-Refaee, 1997). Assuming that the influence of buoyancy has to do with the change of the thermal resistance (thermal diffusivity), the thermal resistance is considered to be small when the buoyancy force is large (Toyoshima et al., 2008). The summary and the comparison of these models are described in the papers (Han et al., 2009; Oliveski et al., 2003; Zurigat et al., 1989). But even in the above investigations, the phenomena of the mass transfer and the thermal diffusion under the condition of the buoyant jet injecting horizontally at the middle of the tank and the jet impinging to the wall are not considered.

In this study, the buoyant jet's influence on the opposite wall was examined in experiments by using tracer particles and thermo-sensitive liquid crystals for visualization of the buoyant jet impinging to the wall and the subsequent thermal diffusion in the 2D cross-sectional area. It was confirmed that, out of this impingement, a vortex is generated steadily near the opposite wall in the buoyant backward direction, and this vortex with height "Z_b" has a relation to the momentum and buoyancy of the buoyant jet. Furthermore, a 3D-CFD was carried out to supplement the 3D behavior of the inner tank fluid. The 1D temperature distribution model, "uniformly distributed injection model", which considered the jet impingement to the wall, was proposed, and the unsteady temperature distributions were verified after comparing them with the experimental results.

2. Buoyant jets

2.1. Parameters of buoyant jets

There are two parameters l_M and l_Q derived by dimensional analysis of buoyant jet characteristics (Fischer et al., 1979). l_M [m] is a characteristic length which has a strong relation to the trajectory of buoyant jets. l_Q [m] is a characteristic length which has a strong relation to the nozzle diameter. l_M is derived by the dimensional analysis using a specific momentum flux and a specific buoyancy flux, and is dependent on the initial value of jet from the nozzle. l_M represents the length of the jet moving horizontally against the buoyancy. If l_M is small, it means the buoyancy force to the fluid is large. l_M can be expressed in the Eq. (1).

$$l_M = \frac{M_J^{3/4}}{B_J^{1/2}} \tag{1}$$

where M_J [m^4/s^2] is a specific momentum flux, B_J [m^4/s^3] is a specific buoyancy flux, and they are defined as:

$$M_J = u_J Q_J \tag{2}$$

$$B_J = g\frac{\Delta\rho_{J,TJ}}{\rho_{TJ}} Q_J \tag{3}$$

$$Q_J = \frac{\pi}{4} D^2 u_J \tag{4}$$

where Q_J [m^3/s] is the volume flow from the nozzle, D is the diameter of the nozzle, andu_J [m/s], g [m/s^2], ρ_{TJ} [kg/m^3], $\Delta\rho_{J,TJ}$ [kg/m^3] denote the velocity defined by the nozzle's cross-sectional area, the gravitational acceleration, the density of water in the tank at the height of the nozzle, the difference in density between the water in the tank at the height of the nozzle and the water being discharged from the nozzle, respectively.

Buoyancy is considered in equations that deal with buoyancy, and in other equations the density is assumed to be a constant. l_Q is represented in Eq. (5) for a round nozzle. It represents the square root of the nozzle's cross-sectional area.

$$l_Q = \frac{Q_J}{M_J^{1/2}} = \sqrt{\frac{\pi}{4}D^2} = \sqrt{\frac{\pi}{4}}D \tag{5}$$

And the internal Froude number Fr ($=u_J/(\Delta\rho_{J,TJ}/\rho_{TJ} g D)^{0.5}$) is defined as below by using l_M and l_Q.

$$\mathrm{Fr} = \left(\frac{\pi}{4}\right)^{1/4}\frac{l_M}{l_Q} = \left(\frac{\pi}{4}\right)^{-1/4}\frac{l_M}{D} \tag{6}$$

Therefore it can be said that Fr has a relation with the dimensionless number l_M divided by the characteristic length D.

$$\mathrm{Fr} \propto \frac{l_M}{D} \propto l_M^* \tag{7}$$

In this paper, the normalized value l_M^* ($=l_M/W_T$) is introduced. l_M^* is recognized to have a relation with Fr.

2.2. Characteristics of buoyant jet and the vortex height Z_b

Fig. 1 shows a schematic drawing of the characteristics of a buoyant jet and a vortex height Z_b, dealt with in this paper. It is the case of a hot (and a high l_M condition) jet discharging into the cold tank water, and impinging on the opposite wall. The trajectory of the buoyant jet is curved upwardly because of a buoyant force. And it impinges on the opposite wall with the horizontal distance from the nozzle equal to the tank width W_T. The buoyant jet is a free jet initially, and changes to an impinging jet, and then to a wall jet. A part of the wall jet makes a vortex near the wall against the buoyancy direction. The height of the vortex's outer edge from the nozzle's central axis is defined as the vortex height Z_b. Let the direction opposite the buoyancy be positive. Z_b means the distance

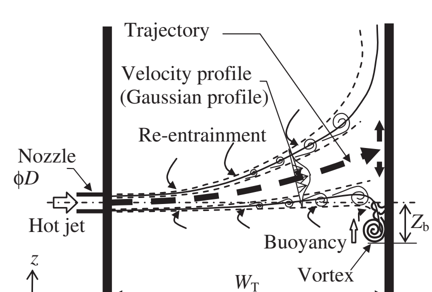

Fig. 1. Schematic of a buoyant jet mode I (influences of an opposite wall on the wall).