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Experimental investigations on turbulent mixing of hot upward flow and cold downward flow inside a chimney model of a nuclear reactor

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HIGHLIGHTS

- Simulated mixing of hot upward and cold downward flows in a chimney of a reactor.
- Experiments in chimney model (2:9 scale) at Reynolds number (Re)—1.5 to 4.5 × 10^5.
- Hot upward flow comes out of the chimney when bypass flow ratio (R) is zero.
- Increase in ratio (R) reduces jet height, vortex spread height and temperature front height.
- Effects of Re, chimney height and temperature differential are not significant.

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ABSTRACT

Experiments were conducted to study the turbulent mixing of hot upward flow and cold downward flow inside a scaled down model of chimney structure of a pool type nuclear research reactor. Open pool type nuclear reactors often use this type of chimney structures to prevent mixing of radioactive core outlet water directly into the reactor pool so that radiation field at the reactor pool top can be kept to a lower limit. The chimney structure is designed to facilitate guiding of the radioactive water towards the two outlet nozzles of the chimney and simultaneously allows drawing water from the reactor pool through the chimney top opening. The present work aims at studying flow mixing behaviour of hot and cold water inside a 2/9th scaled down model of the chimney structure experimentally. The ratio between the cold downward flow and the hot upward flow is varied between 0 and 0.15 to predict the extent of suppression of the hot upward flow within the chimney region for various bypass flow ratios. The Reynolds number of the hot upward flow considered in the experiment is about 1.5 × 10^5 which corresponds to a flow rate of about 500 l min^{-1}. The upward jet height and the temperature distribution were predicted from the experiment. It was observed that increase in bypass flow ratio reduces the upward jet height of hot water. Experiments were also carried out by increasing the flow rate to 1000 and 1500 l min^{-1} corresponding to Reynolds numbers of 3 × 10^5 and 4.5 × 10^5, respectively. It was observed that the jet height did not vary significantly with changing upward flow rate provided the bypass flow ratio was held constant. Experiments were also done by increasing the chimney height from 500 mm to 600 mm and no significant change in mixing behaviour of the hot and cold water was observed.

1. Introduction

Experimental investigations were carried out to study the turbulent mixing behaviour of hot upward flow and cold downward flow inside a scaled down (2:9) model of the chimney structure of the High Flux Research Reactor (Chafle et al., 2009) being developed at BARC. The reactor core is cooled by forced upward flow of water through the core. After passing through the reactor core, water becomes radioactive due to formation of radio-nuclides (N^{16}, O^{19}, Na^{24}, Ar^{41} etc.) by nuclear reactions with neutrons present in the core. Because of the higher flow velocity of radioactive water in the upward direction, it has a tendency to reach towards the

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Nomenclature

D	side of square chimney (m)
H	height of chimney (m)
h_j	upward jet height (m)
h_s	vortex spread height (m)
h_T	temperature front height (m)
R	bypass flow ratio (W_{in}/W_{bp})
R^2	coefficient of determination
Re	Reynolds number ($\rho U_{in} D/\mu$)
T	water temperature (°C)
T^*	dimensionless temperature $(T - T_c)/(T_h - T_c)$
U	upward fluid velocity (m s^{-1})
W	mass flow rate (kg s^{-1})
y	height along upward direction (m)
y^*	dimensionless height (y/D)

Symbols

μ	viscosity (kg m^{-1} s^{-1})
ρ	fluid density (kg m^{-3})

Subscripts

bp	bypass flow
in	inlet
p	pool

pool top due to its inertia. This results in high radiation level at the pool top. Since, pool top activity level should be limited during normal operation; these reactors often use a chimney structure at the reactor core outlet in order to prevent radioactive coolant reaching the pool top. This chimney structure facilitates guiding of the radioactive water from the reactor core towards the side outlets of the chimney and simultaneously allows drawing water from the reactor pool through the chimney top opening. As the radioactive water flows upward and has a tendency to reach to the pool top through the chimney top opening (provided for handling fuel and isotope assemblies), pool water flowing in the downward direction is desirable to suppress the upward flowing hot radioactive water. This downward flow through the chimney is compensated by providing additional core bypass flow to the pool. A delicate balance between these two opposing flows–hot water from the core outlet (upward flow) and relatively cold water from the pool (the downward core bypass flow) is required to prevent the radioactive hot water reaching the reactor pool.

The basic function of the chimney is to guide the radioactive water from the core outlet to the two side outlets of the chimney which is connected to the suction of a set of primary coolant pumps. The core outlet water is drawn via the chimney by these pumps to provide forced cooling through the reactor core. The core outlet water being radioactive is passed through a set of delay tanks to decay down the activity level mainly caused by N^{16} radio-nuclides. Subsequently the primary coolant water is sent through a set of heat exchangers where heat is transferred to a secondary coolant (cooling tower water). The cold primary coolant water from the outlet of the heat exchangers is fed back to the inlet plenum at the bottom of the reactor core. A part of the cold water (called core bypass) is also sent to the reactor pool (the water pool where the reactor core is submerged). The core bypass water is drawn inside the chimney through the top opening by dynamic balancing. The core bypass water flows in the downward direction and suppresses the upward radioactive core outlet water well within the chimney so that no radioactive water can reach the reactor pool top through the top opening of the chimney. During normal operation (with main coolant pumps operating) as well as shut down condition of the reactor (with auxiliary coolant pumps operating), the chimney is used to provide its desired function of suppressing the radioactive water within the chimney so that radiation field at the pool top can be well within limit. Detailed description of the primary coolant system of HFRR is reported by Sengupta et al. (2013d).

Though an open chimney structure is used by some nuclear research reactors (e.g., ETRR-2, HANARO, OPAL), literature on mixing behaviour inside the chimney structure and its dependence on flow ratios between cold and hot fluids, temperature differentials as well as heights of the chimney are limited. For closure flow inside the chimney, a numerical study of steady, incompressible flow for two-dimensional geometry for ETRR-2 reactor was reported by El-Morshdy (2007). However, investigations on mixing of confined jets in various geometries (X-junction, T-junction) which have similarity with mixing of hot and cold streams inside chimney, were reported by various researchers.

Mixing of turbulent (Re = 30,000) opposing jets was numerically simulated using low Reynolds κ–ε turbulence models by Wang and Mujumdar (2005) for pure water and sodium chloride solution. After impingement in the mixer, the combined fluid leaves symmetrically via two symmetric exit channel outlets. Total exit mass flow rate was kept constant and the ratio of inlet mass flow rate of two jets was varied from 1.0 to 1.5. Turbulent (Re = 40,000) mixing of two streams (inlets at right angle) was simulated using large eddy simulation (LES) approach by Webb and Waanders (2006) for pipe cross geometry. Turbulent mixing in a pipe line of X-junction was reported by Vicente et al. (2008) where both the pipes were used to transport clean water but a specified concentration of a passive scalar was added in one of the two inlets. The angle between the two inlets was 90°. Flow rate of inlet-1 was constant (Re = 28,000) and flow rate of inlet-2 was varied (Re 23,000 to 50,000). Numerical simulation of turbulent mixing using standard κ–ε model was experimentally validated by measuring the concentrations.

Numerical simulation of two opposing air jets (cold jet at 304 K and hot jet at 315 K) was carried out by Wang and Mujumdar (2007) for dual-inlet inline mixer. Standard κ–ε turbulence model was used to model the turbulent mixing (Re = 35,000) and Validation was done by comparing the predicted temperature profiles with published experimental results for a T-junction. An experiment of mixing of cold water (main flow) with hot water (branch flow) in a T-junction with a 90° bend upstream was performed by Hosseini et al. (2008) using the PIV technique to visualise the flow characteristics in T-junction area (Re = 33,000–150,000). Mixing of hot water at 48 °C and cold water at 33 °C in a T-junction was experimentally and numerically investigated by Kamide et al. (2009) with maximum main flow (Re = 435,000) and branch flow (Re = 75,000). Temperature distribution and velocity field were measured by a movable thermocouple tree and the PIV technique, respectively. Mixing of cold water and hot water in a T-junction test section was numerically simulated and experimentally validated by Naik-Nimbalkar et al. (2010). Steady state three dimensional numerical simulations were carried out using standard κ–ε turbulence model to predict the mean velocity and temperature. Velocity and temperature measurements were carried out using hot-wire anemometer and good agreement was reported with the numerical results. Mixing in a T-junction with each branch of 50 mm diameter was simulated by Stigler et al. (2012) numerically using κ–ε realizable turbulence modeling with non-equilibrium wall functions. Flow ratios were varied from 0 to 1 in steps of 0.2. Experiments were done using the PIV technique and good agreement was reported with numerical results.

Numerical simulations were reported for a circular chimney structure by Sengupta et al. (2013a) using standard κ–ε turbulence model and results for the prototype chimney and 1/6th scaled down model were discussed. Effect of increase in bypass flow towards preventing the radioactive coolant reaching the pool top