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Numerical simulations of a mixed momentum-driven and buoyancy-driven jet in a large enclosure for nuclear reactor severe accident analysis

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HIGHLIGHTS

- Simulations of thermal stratification in large enclosures using different turbulence models.
- The recent elliptic blending k–ε was implemented in this work.
- Direct comparisons of experimental temperature measurements to CFD predictions.
- Spurious prediction of jet stabilisation and diffuse stratification by both low-Re k–ε and SST k–ω.

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ABSTRACT

An ability to predict the behavior of buoyant jets entering a large body of relatively stationary fluid is important in analysis of a wide variety of nuclear accidents, including for example the use of large tanks of water as heat sinks, or the release of hot gases into the secondary containment. In particular, the degree to which temperature stratification occurs is important, as it can affect markedly the effectiveness of the body of fluid as a heat sink. In this paper, we report the results of measurements on an experimental facility designed to exhibit such behavior, and the results of attempts to predict this experiment using CFD. In particular, we here investigate the effectiveness of three alternative turbulence models for this analysis; low-Re k–e, elliptic-blended k–e and Shear Stress Transport k–ω models. Both the degree of thermal stratification and the stability of the jet that were predicted differed markedly between the three models. Two of the models, the low-Re k–e and the Shear Stress Transport k–ω, tend to predict, wrongly, significant turbulent intensity in regions where fluid velocities are essentially zero. This spurious high turbulent intensity in turn causes (i) a high turbulent viscosity to be applied, wrongly stabilizing the jet, and (ii) increased turbulent diffusion of heat, causing too deep and diffuse a stratification to be predicted.

1. Introduction

In large enclosures such as a nuclear reactor containment building or spent fuel pool, a single jet of hotter fluid can lead to thermal stratification. Such stratification can reduce passive heat transfer, contribute to structural damage, and lead to high concentrations of hazardous chemical and radioactive species (Zhao and Peterson, 2010). Zhao et al. discusses, for instance, the effect of thermal stratification within a boiling water reactor suppression pool during a severe accident, where steam is injected into the pool to reject heat from the reactor vessel (Zhao et al., 2014). Severe accidents involving such phenomena can also occur with other types of reactors such as sodium fast reactors (SFRs), and molten salt reactors (MSRs). For example, in a prototypical SFR pool design, a volume of sodium co-exists with an upper layer of argon gas, creating a free surface between the two fluids (Tenchine, 2010). During severe accidents such as loss of flow transients, heated sodium from the core will rise and possibly collect at the top of the upper plenum, which could cause significant thermal stresses. This configuration is particularly relevant to the present

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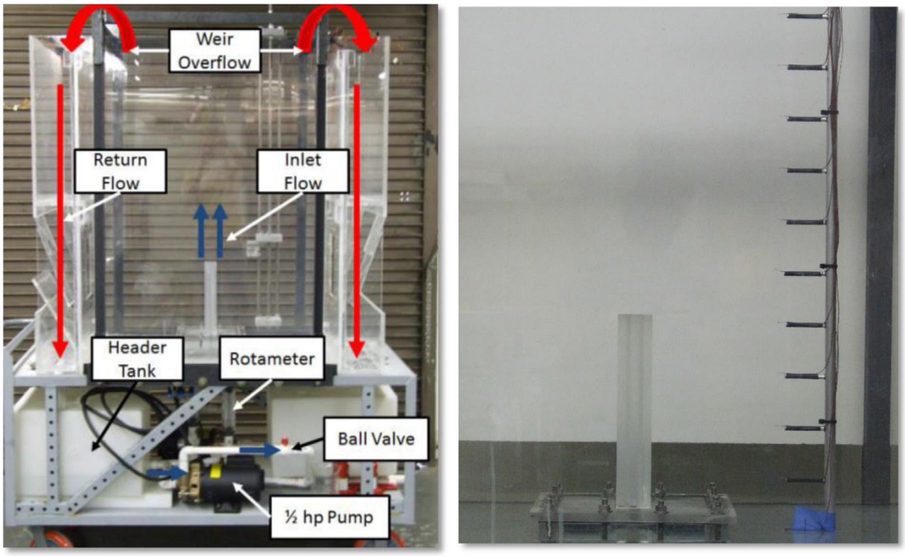

Fig. 1. Twin jet water facility and instrumentation for thermal stratification studies.

work. Zhao and Peterson note that in molten salt reactors (MSR) prevention of thermal stratification is necessary for effective natural convection cooling during shutdown and transients (Zhao and Peterson, 2009).

In the present work, a rectangular jet of hot water injected from below into a large quiescent pool of cold water is considered. Such jets of hot fluid are initially momentum-driven, but will ultimately be driven by buoyancy alone. The co-existence of laminar and turbulent regions, as well as the large degree of anisotropy inherent in any buoyancy driven flow, makes the accurate simulation this particularly challenging. Kumar and Dewan reviewed advances in computational modeling applied to turbulent thermal plumes. This review includes modeling efforts using direct numerical simulations (DNS), large eddy simulations (LES), and Reynolds Averaged Navier-Stokes (RANS) approaches (Kumar and Dewan, 2014a). In their review of RANS modeling approaches, they focused on the various approaches to model the turbulent heat fluxes and the associated buoyancy production/destruction terms that arise in the turbulent kinetic energy and dissipation rate equations, in the presence of density variations. Their review is mainly focused on the standard k–ε and realizable k–ε models. These remain among the most widely used in the engineering community, despite the numerous deficiencies in these models highlighted over the years by researchers attempting to simulate buoyancy driven flows.

Outside the k–ε turbulence model family, the k–ω turbulence model has been used to simulate both turbulent jets and plumes by Malin and Spalding, who found this model to give reasonable agreement with experimental data (Malin and Spalding, 1984). With regards to the modeling of turbulent heat fluxes, which is necessary to bring proper mathematical closure to the mean energy equation, three main approaches are employed in the literature on buoyancy driven flows. The simplest approach is the single gradient diffusion hypothesis (SGDH), which simply links the turbulent heat fluxes to the eddy viscosity through the introduction of a turbulent Prandtl number. This assumes the turbulent heat fluxes are aligned with the temperature gradient. In order to overcome deficiencies of the SGDH, (Ince and Launder, 1989) applied the generalized gradient diffusion hypothesis (GGDH) which introduces a cross-stream temperature gradient into the turbulent heat flux formulation. This approach is robust computationally but unfortunately rarely implemented in commercial CFD codes[1]. A more refined approach is the algebraic flux model (AFM), which can be seen as an extension of the GGDH formulation requiring an additional transport equation for the temperature. The latter generally improves the accuracy of the prediction but tends to reduce the robustness of the system. Kumar et al. mention that when the SGDH formulation is used, the buoyancy term in the turbulent dissipation rate equation does not contribute significantly to the dissipation and can probably be ignored. When using the GGDH formulation however, this is not so, and it is required for proper implementation of this approach (Kumar and Dewan, 2014b).

The present work focuses on simulating the buildup of the stratified layer and the buoyant jet behavior. It is important to compare the performance of commonly used turbulence models in order to gain confidence in the modeling approach for such flows.

Three turbulence models are compared here:

(i) Low-Re k–ε (Lien et al., 1996).
(ii) Shear Stress Transport (SST) k–ω (Malin and Spalding, 1984).
(iii) The recently-proposed elliptic blending k–ε (EB k–ε) from (Billard and Laurence, 2012).

In the present case, the SGDH formulation will be used for all simulations (excluding SST k–ω), as this remains the only choice available in most commercial CFD codes. The aim of the present work is therefore to investigate the relative performance of these three approaches to predict thermal stratification in large enclosure.

The present paper is organized as follows. The experimental facility is described in Section 2. The approach adopted in the modeling is outlined in Section 3. The comparison between the experimental data and the predictions obtained using the various modeling approaches is presented in Section 4, and conclusions are drawn in Section 5.

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[1] The GGDH and AFM model are both actually available in STAR-CCM+, used in the present work, but for the Low-Re k–ε treatment from Lien et al. only. This model is also only available when the Boussinesq assumption is invoked for the buoyancy source term, which precluded its use in the present study.

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