Analytical and Experimental Investigation of Mixing in Large Passive Containment Volumes

1st Year NEER Progress Report

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This progress report details results from the first year of the three-year UC Berkeley NEER investigation of mixing phenomena in large-scale passive reactor containments. We have completed all of our Year-1 deliverables specified in our proposal, as summarized for each deliverable in the body of this report, except that we have delayed three months in reconfiguring our enclosure experiment to gather additional data. We have particularly exciting results from this experiment studying the forced-convection augmentation by jets of natural convection heat transfer to containment walls and structures. These experiments now have shown why augmentation has been observed in wall-condensation experiments due to the momentum of the steam break-flow entering large volumes. More importantly, we also have shown that the forced-jet augmentation can be predicted using relatively simple correlations, and that it is independent of the break diameter and depends only on the break flow and momentum. This suggests that we will now be able to take credit for this augmentation in reactor safety analysis, improving safety margins for containment structures.

Passive containments, which use natural circulation to remove decay heat following an accident, provide the greatest promise for nuclear energy to repenetrate U.S. and European markets that have not seen new plant orders in two decades. The first plants reentering these markets will likely be LWRs, where proven reactor technology and licensing reduce financial risk. Innovative passive containments for these LWRs can provide strong public confidence in safety, as well as reduce plant cost (for a given reactor size).

INTRODUCTION

The principal purpose of the UC Berkeley NEER research is to improve understanding and modeling capabilities for mixing and heat/mass transfer to walls and structures in large containment volumes, as illustrated schematically in Figure 1. Two conditions are typically observed in such volumes, either a zero-dimensional well-mixed state where lumped treatment of the volume's mass and energy provides an accurate treatment of the conservation equations, or stratified conditions where substantial vertical temperature and concentration gradients may exist, particularly where mass may "hide out" in stagnant stratified regions, and where vertical transport occurs in relatively thin wall and free buoyant jets. In the second case substantial challenges exist to model the transport processes with three-dimensional codes, because the finite-difference treatments generate substantial artificial diffusion which smears greatly the sharp gradients that exist in physical systems. The UC Berkeley BMIX code approach uses integral models to treat the wall and free buoyant jets, allowing their detailed structure to be treated accurately, and one-dimensional Lagrangian modeling of the stratified ambient. Over the last year we have demonstrated that this method can eliminate the effects of numerical diffusion, down to the numerical precision of computers used for the computation (Christensen and Peterson, 1999). We have also demonstrated excellent agreement between the numerical model and analytical and experimental data.

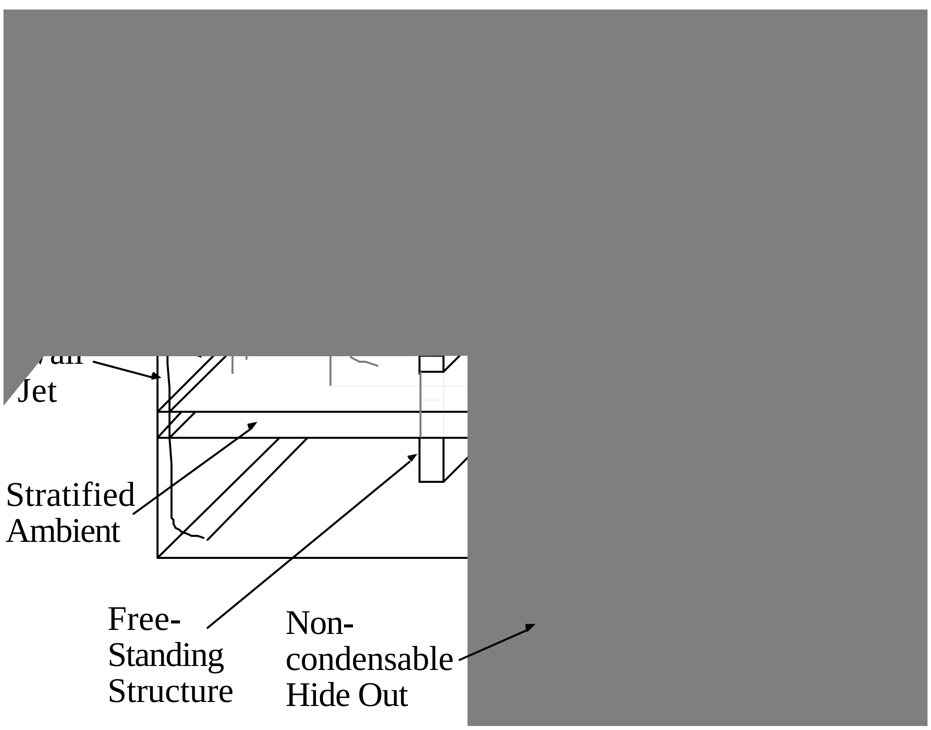

Fig. 1 Schematic of jet mixing processes in a large containment volume.

Currently four graduate students and one postdoctoral researcher are working on the modeling and experimental efforts. Two senior doctoral students will complete dissertations over the coming year. One senior student, funded by General Electric, is focusing attention on the scaling methodology for modeling complex mixing and transport phenomena. The second senior student, funded by near, has developed the computation models reported here. Two new doctoral students have started work over the last year as well, one focusing on modeling and the other on the supporting experimental studies.

YEAR-ONE DELIVERABLES RESULTS

Modeling Tasks

1) *Equations of State and Compressibility Effects (YEAR 1).*
Deliverable: Conference/archival paper on topic of incompressible modeling of compressibility effects (quasi-steady modeling); summary of modeling method in annual progress report.

This paper describing the numerical implementation of the new computational approach, and comparisons with experimental and analytical predictions, was completed and presented at the NURETH-9 conference in San Francisco, and was accepted for archival publication in Nuclear Engineering and Design (Christensen and Peterson, 1999). The method to be employed to incorporate compressibility effects has also been developed. The important insight is that while unequal inflow and outflow from a volume can force compression of the gas in the volume, the flow is not compressible in the standard sense, and is best treated as a quasi-incompressible fluid where pressure signals transmit instantly and the fluid inventory compresses uniformly to accommodate inventory changes. To implement the solution numerically, the standard incompressible algorithm is used for each time step, so that inventory changes in the Lagrangian treatment cause the total volume of the system to change. A corrector step is then employed to correct the volume pressure to restore the correct total volume, changing the volume of each Lagrangian zone to reflect the equation of state of the gas species.

2) *Develop Library of Free-Jet Models (ONGOING YEAR 1, 2, 3).*
Deliverable: Include models in relevant conference/archival papers; summarize new models in annual progress reports.

One of the new doctoral students has completed a comprehensive survey of modeling methods for buoyant free and wall jets from literature from 1979 through the present This student is now developing a suite of integral models to be used in the BMIX code.

3) *Develop Library of Wall-Plume Entrainment, Heat Transfer and Condensation Models (ONGOING YEAR 1, 2, 3).*
Deliverable: Include models in relevant conference/archival papers; summarize new models in annual progress reports.

See (3) above.

4) *Coupling to Integral Thermal Hydraulics Codes (YEAR 2).*
Deliverable: Discuss effectiveness of coupling in relevant conference/archival papers; publish final code in final report and make available on web.

To be reported in one year.

5) *Algorithms for Multiple Large Volumes (YEAR 3).*
Deliverable: Include models in relevant conference/archival papers; summarize new models in annual progress reports.

To be reported in one year.

Experimental Tasks

1) *Forced-jet augmentation of natural convection heat transfer (YEAR 1).*
Deliverable: Present experimental results and comparison to models in relevant conference/archival papers; publish experimental results in progress report and make available on web.

Two years ago we reported evidence from limited experiments reported in the chemical engineering literature on forced convection heat transfer induced in vessels by jet injection (Peterson and Gamble, 1998), that when presented in nondimensional form, the forced-convection augmentation of natural convection would take a very simple form. The potential for this result is important, since break flows in reactor containments have been postulated to be important sources of heat and condensation mass transfer augmentation. This effect, for example, was postulated as the reason for higher condensation mass transfer being observed in AP-600 containment condensation experiments than would be predicted by standard natural convection correlation for noncondensable gas effects (Woodcock et al., 1999). However, no information has been available to predict the augmentation effect, or to predict how it scales from test facilities to full-scale systems. Thus in addition to not being able to take credit for the augmentation effect, questions exist as to whether it is conservative to apply condensation results from scaled facilities, where augmentation is known to occur due to the momentum of the injected steam jet, to a full scale facility where the injected momentum may be larger or smaller.

Figure 2 illustrates the experimental results we have obtained in an extensive series of experiments over the last year, investigating the augmentation of heat transfer from the heated bottom surface of a 3.0-m diameter, 1.2-m high cylindrical enclosure where an air jet with varying momentum is injected either radially, azimuthally, or vertically into the volume. We find that the augmentation depends only on the direction of injection and on the Archimedes number (Re^2/Gr), and not directly on the Reynolds number or the diameter of the jet. This means that the heat transfer augmentation by injected jets can be bounded, and is relatively independent of the size of the enclosure when correlated by the Archimedes number. Furthermore, we have confirmed that our experimental conditions bound the range of Archimedes number values expected for passive containment systems like the SBWR and AP-600.

We have extended the number of experiments that we are performing in the cylindrical enclosure, prior to tearing it down and refabricating a rectangular enclosure to use for vertical-wall experiments with varying enclosure aspect ratio. Currently, we are placing arrays of vertical tubes in the cylindrical enclosure to provide a distributed momentum sink, to study the likely effects of structures (pipes, walkways, stairs, railings, equipment) in altering or reducing the effectiveness of large-scale forced convection motion in augmenting heat transfer. Because this is a potentially important issue, we felt that it justified the resulting delay in the vertical wall experiments.

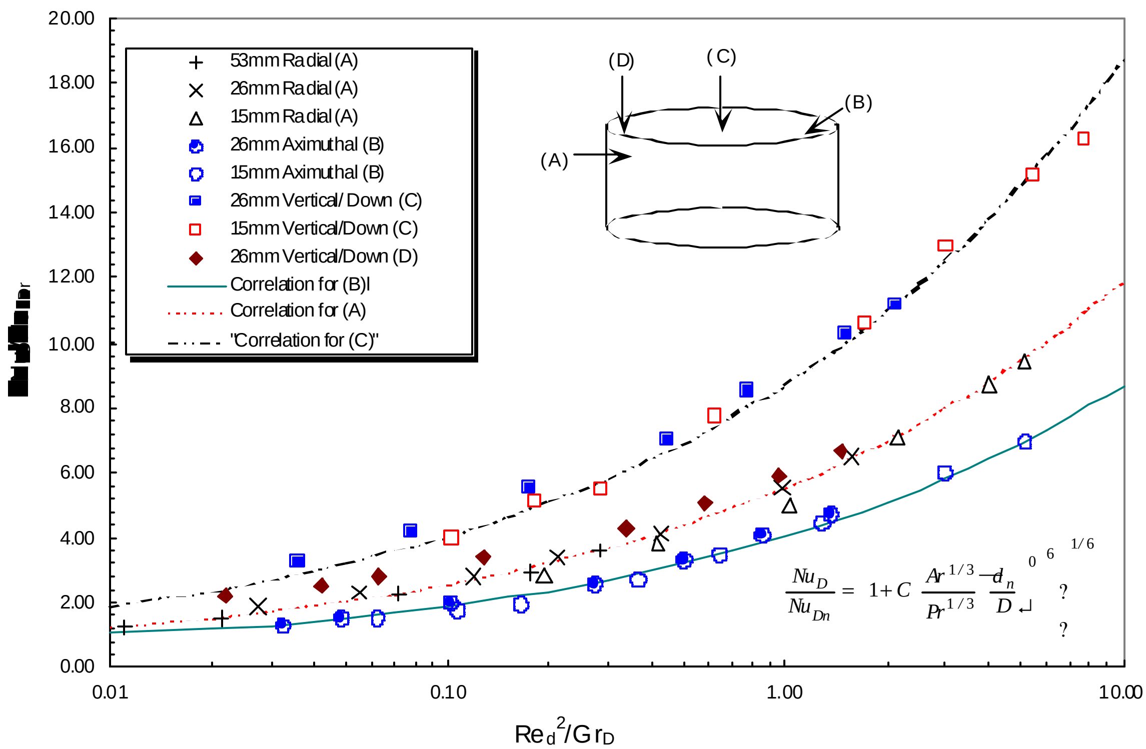

Fig. 2 Forced-convection augmentation of heat transfer from the heated bottom surface in a large cylindrical enclosure by an injected jet (results not yet published), normallized by the pure natural convection value from standard correlations.

2) *Effects of enclosure aspect ratio on onset of stratification (YEAR 1).* Deliverable: Present experimental results and comparison to models in relevant conference/archival papers; publish experimental results in progress report and make available on web.

As discussed in (2) above, we have delayed 3 months in reconfiguring our experimental apparatus to gather additional data for the effects of distributed resistance in changing forced-convection augmentation. These additional experiments will be complete by the end of June, and the reconfiguration of the experiment will be complete by August, 2000.

3) *Turbulence Effects on Mixing and Heat Transfer (YEAR 2).* Deliverable: Present experimental results and comparison to models in relevant conference/archival papers; publish experimental results in progress report and make available on web.

To be reported in one year.

4) *Steam Condensation in the Presence of Noncondensable Gas (YEAR 3).* Deliverable: Present experimental results and comparison to models in relevant conference/archival papers; publish experimental results in progress report and make available on web.

To be reported in one year.

References

J. Christensen and P.F. Peterson, "A One-Dimensional Lagrangian Model for Large-Volume Mixing," Ninth International Topical Meeting on Nuclear Reactor Thermal Hydraulics, San Francisco, California, October 3 - 8, 1999. (to appear in *Nuclear Engineering and Design*).

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