STUDY OF ABNORMAL HEAT TRANSFER DURING FORCED AND NATURAL CONVECTION SCENARIOS IN A PRISMATIC CORE OF A VHTR: NUMERICAL AND EXPERIMENTAL RESULTS

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ABSTRACT

Very High Temperature Reactors (VHTRs) are one of the Generation IV gas-cooled reactor models proposed for implementation in next generation nuclear power plants. A high temperature/pressure test facility for forced and natural circulation experiments has been constructed. This test facility consists of a single flow channel in a 2.7 m (9') long graphite column equipped with four 2.3kW heaters. Extensive 3D numerical modeling provides a detailed analysis of the thermalhydraulic behavior under steady-state, transient, and accident scenarios. In addition, forced convection experiments with air and nitrogen were conducted for inlet Reynolds numbers from 1,500 to 70,000. Numerical results, using commercial finite element package, COMSOL Multiphysics, were validated with forced convection data displaying maximum percentage errors under 15%. Based on this agreement, simulations are also extended to study natural circulation of nitrogen and helium between two connected vessels, resembling the behavior between inner and outer cooling channels in a VHTR reactor core. Results were obtained for Rayleigh numbers of ~10^6. This work also examines flow laminarization for a full range of Reynolds numbers including laminar, transition and turbulent flow under forced convection and natural circulation and its impact on heat transfer under various scenarios to examine the thermal-hydraulic phenomena that could occur during both normal operation and accident conditions.

KEYWORDS

Forced convection, heat transfer, VHTR, high temperature gas reactor

1. BACKGROUND

Very High Temperature Reactors (VHTRs) are one of the Generation IV reactors that have been proposed for DOE's Next Generation Nuclear Plant. Several characteristics have stimulated this development including higher efficiencies due to higher working temperatures and the additional benefits of passive safety systems including intracore conduction and natural circulation for decay heat removal and dissipation in accident scenarios. Key phenomena have also been identified as leading to localized hot spots in the nuclear reactor, including: degraded heat transfer in coolant channels, laminarization of flow, effects of bypass flow, and non-uniform heat generation across the core.[1-2]

One issue in studying flow laminarization is implementing applicable turbulence models with appropriate parameters. Mikielewics et al. [3] successfully studied internal velocity and temperature fields of strongly heated internal flows numerically. They examined eleven turbulence models, requiring two partial differential equations or less. They concluded that the model by Launder[4] performed best in predicting experimental data.[3] Their study highlights the difficulty involved in modeling even simple axisymmetric gas flows in pipes subjected to intense heating, which take into account variable gas properties since only one out of the eleven models agreed on heat transfer parameters such as the Nusselt number. Several of these other k-ε models specifically developed for low Reynolds number applications even gave unacceptably high Nusselt number predictions.[3] In addition, many of these studies were specific to the conditions used in the experiments of Shehata and McEligot.[5,6], thus the knowledge base available outside the conditions used in Shehata and McEligot's experiments is limited. This points to the limited range of applications of even the successful models, since their validation data was constrained to small tubes, low

4. The fluid flow model (laminar, *k*-*ε* and low Re *k*-*ε* turbulence models) used in numerical simulations had a minor impact on the Reynolds number predictions (<1.5% difference) but as much as a 15% difference in the Nusselt number predictions.

Future work includes further CFD model validation based on experimental data and carrying simulations for helium as the working fluid.

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REFERENCES

1. Ball, S.J., and Fisher S.E., "Next-Generation Nuclear Plant (NGNP) Phenomena Identification and Ranking Table (PIRT) for Accident and Thermal Fluids Analysis," NUREG/CR-6944, 2007.
2. McEligot, D.M., and Banston, C.A., "Numerical Predictions for Circular Tube Laminarization by Heating," NASA Center, ASME Paper 69-HT-52, 1969.
3. Mikielewicz, D.P., Shehata, A.M., Jackson, J.D., and McEligot, D.M., "Temperature, velocity and mean turbulence structure in strongly heated internal gas flows: Comparison of numerical prediction with data," Int. J. Heat and Mass Transfer 45, 4333-4352, 2002.
4. Launder, B.E., "Laminarization of the turbulent boundary layer by acceleration", Technical Report 77, MIT Gas Turbine Lab, 1964.
5. Shehata, A.M., "Mean Turbulence Structure in Strongly Heated Air Flows," Ph.D. thesis, University of Arizona, Tucson, U.S.A., 1984.
6. Shehata, A.M. and McEligot, D.M., "Mean structure in the viscous layer of strongly heated internal gas flows. Measurements," Int. J. Heat Mass Transfer 41, 4297-4313, 1998.
7. Valentín, F. I., Artoun, N., Bindra, B., and Kawaji, M., "Investigation of flow Laminarization and Heat Transfer Reduction in a VHTR Reactor Core". Submitted to ANS Winter Meeting and Technology Expo - 2014, Anaheim, California, November 9-13, 2014.
8. COMSOL Multiphysics Reference Manual, Stockholm, Sweden, 2007.
9. Monarch Instrument. *http://www.monarchserver.com/TableofEmissivity.pdf* Web. 30 Jan. 2015.
10. Incropera, F.P., and Dewitt, D.P., Fundamentals of Heat and Mass Transfer, 5th ed., John Wiley & Sons, 2002.
11. Valentín, F.I., Artoun, N., Kawaji, M., and McEligot, D.M., "Experimental Study of forced convection heat transfer during upward and downward flow of helium at high pressure and high temperature," Submitted to ASTFE Engineering Summer Conference Expo- 2015, New York, August 9-12, 2015.
12. Holman, J.P., Heat Transfer, 9th ed., McGraw-Hill, New York, 2002.
13. McEligot, D.M., Shehata, A.M., Webster, N.Y., and Kunugi, T., "Prediction of strongly-heated gas flows," INEEL/CON--97-01336, 1997.
14. McEligot, D.M., Magee, P.M., and Leppert, G., "Effect of Large Temperature Gradient on Convective Heat Transfer: The Downstream Region," Journal of Heat Transfer, 87, 67-76, 1965.
15. Taylor, M.F., "Experimental Local Heat Transfer Data for Precooled Hydrogen and Helium at Surface Temperatures up to 5300 R," NASA-Lewis Research Center Technical Note TN D-2595, 1965.
16. Taylor, M.F., "Correlation of Local Heat-Transfer Coefficients for Single-Phase Turbulent Flow of Hydrogen in Tubes with Temperature Ratio of 23," NASA-Lewis Research Center Technical Note TN D-4332, 1967.
17. Dalle Donne, M. and Meerwald, E., "Experimental Local Heat-transfer and Average Friction Coefficients for Subsonic Turbulent Flow of Air in an Annulus at High Temperatures," Int. J. Heat Mass Transfer, 9, 1361-1376, 1966.
18. Dalle Donne, M. and Meerwald, E., "Heat-transfer and Friction Coefficients for Turbulent Flow of Air in smooth Annuli at High Temperatures," Int. J. Heat Mass Transfer, 19, 787-809, 1973.
19. Olson, D.A. and Grover, M.P., "Heat Transfer in a Compact Tubular Heat Exchanger with Helium Gas at 3.5 MPa," National Institute of Standards and Technology Report NISTIR 3941, 1990.
20. Travis, B.W. and El-Genk, M.S., "Numerical Simulation and Turbulent Convection Heat Transfer Correlation for Coolant Channels in a Very-High-Temperature Reactor," Heat Transfer Engineering, 34(1), 1-14, 2013.
21. W.B. Hall, J.D. Jackson, Laminarization of a turbulent pipe flow by buoyancy forces, ASME 69-HT-55, 1969.
22. McEligot, D.M., Coon, C.W., and Perkins, H.C., Relaminarization in tubes, Int. J. of Heat Mass Transfer 13 (1969) 431–433.
23. Bejan, A., Heat Transfer, Wiley, New York, 1993.