INEEL/CON-05-02591
PREPRINT

Idaho National Engineering and Environmental Laboratory

Key Thermal Fluid Phenomena in Prismatic Gas-cooled Reactors

Donald M. McEligot
Glenn E. McCreery
Paul D. Bayless
Theron D. Marshall

June 2005

ANS Annual Meeting

Key thermal fluid phenomena in prismatic gas-cooled reactors*

Donald M. McEligot, Glenn E. McCreery, Paul D. Bayless and Theron D. Marshall

Idaho National Engineering and Environmental Laboratory (INEEL),
Idaho Falls, Idaho 83415-3885 (dm6@inel.gov)

INTRODUCTION

Several types of gas-cooled nuclear reactors have been suggested as part of the international Generation IV initiative with the proposed NGNP (Next Generation Nuclear Plant) as one of the main concepts [MacDonald et al., 2003]. Meaningful studies for these designs will require accurate, reliable predictions of material temperatures to evaluate the material capabilities; these temperatures depend on the thermal convection in the core and in other important components. Some of these reactors feature complex geometries and wide ranges of temperatures, leading to significant variations of the gas thermodynamic and transport properties plus possible effects of buoyancy during normal and reduced power operations and loss-of-flow (LOFA) and loss-of-coolant scenarios. Potential issues identified to date include "hot streaking" in the lower plenum evolving from "hot channels" in prismatic cores. In order to predict thermal hydraulic behavior of proposed designs effectively and efficiently, it is useful to identify the dominant phenomena occurring.

APPROACH

For heated flow in vertical cooling channels, McEligot and Jackson [2004] have presented the non-dimensional governing parameters which indicate when a phenomenon -- such as gas property variation, streamwise acceleration or buoyancy -- may lead to increases in wall temperature above those predicted with popular correlations and turbulence models. For normal operating conditions and loss-of-flow transients, helium flow conditions have been predicted via systems codes for the NGNP [McEligot and McCreery, 2004] and for a gas fast-spectrum reactor (GFR) concept proposed by Williams et al. [2003]. From these predictions, magnitudes of these parameters were estimated. Approximate analyses were also applied to identify key phenomena in a typical NGNP lower plenum during normal operations.

RESULTS

For the cooling channels of the NGNP Point Design [MacDonald et al., 2003], order-of-magnitude estimates of the non-dimensional heat flux for nominal full power and reduced power are presented in Figure 1. Highest gas bulk temperatures occur at the outlet from the active core. The range of outlet Reynolds numbers varied from about 57,000 for a high power core to about 2300 at ten per cent power. In all cases calculated, q^+, K_v and Bo* were low relative to their thresholds for significant effects. A low value of q^+ implies that gas property variation across the channels would have only a slight effect on the local Nusselt number and friction factor. The acceleration parameter K_v provides a measure of the likelihood of laminarization due to streamwise acceleration induced by the reduction in gas density with heating. Likewise, the buoyancy parameter Bo* indicates whether the heat transfer parameters may be enhanced or reduced as a consequence of buoyancy influences. *For the proposed diameters* of the coolant channels in the NGNP Point Design, **neither** property variation, acceleration **nor** buoyancy would be expected to have significant effects in normal full-power operations.

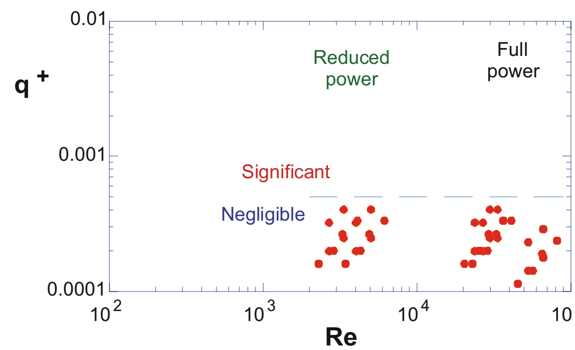

Fig. 1. Expected order-of-magnitude of non-dimensional heat flux (indicator of significance of transverse property variation) during normal operating conditions in NGNP Point Design.

For a hypothesized LOFA scenario, the Reynolds number decreases to below 2000 within about sixty seconds and then remains below an absolute value of about 500, indicating that laminar flow would be likely. During the first twenty minutes or so, magnitudes of the appropriate laminar buoyancy criterion [Scheele and Hanratty, 1962] indicate the possibility of asymmetric flow at some locations and a need for a three-dimensional solution allowing for separation (Figure 2). Laminar flow instability [Bankston, 1965; Reshotko, 1967; Black, Klinzing and Therney, 1977; Hejzlar, Williams and Driscoll, 2004] may also become a concern and warrants further study.

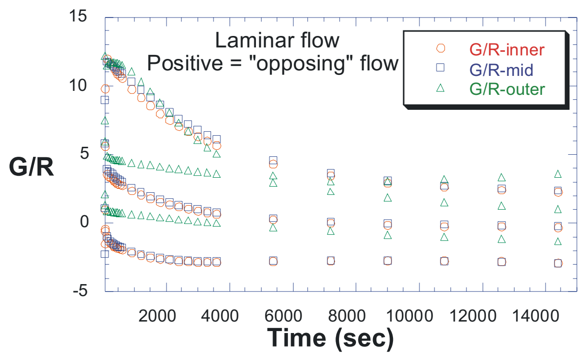

Fig. 2. Estimated buoyancy trends during a hypothetical loss-of-flow scenario in NGNP Point Design.

The flow in the **lower plenum** can locally be considered to be a situation of multiple buoyant jets into a confined crossflow -- with obstructions. Results of an approximate analysis indicated that the jets can be expected to be momentum-driven in normal operations. A second approximate analysis was conducted to estimate when a temperature gradient will stabilize a horizontal turbulent channel flow, thereby leading to reduced thermal transport near the upper surface; near the plenum outlet duct, buoyancy effects were predicted to be negligible.

For the **GFR** of Williams et al. [2003] with helium as a coolant, predictions for full power and during a LOFA scenario show that the non-dimensional heat flux is expected to exceed its threshold (Figure 3) and lead to reduced Nusselt numbers [McEligot, Magee and Leppert, 1965]. The difference from the NGNP case is due to the higher power density of the GFR. While the flow is turbulent, the Jackson buoyancy parameter is estimated to be below its threshold for significant effects. However, during the natural circulation in the later stages of the LOFA scenario, laminar flow instability may become important [Hejzlar, Williams and Driscoll, 2004].

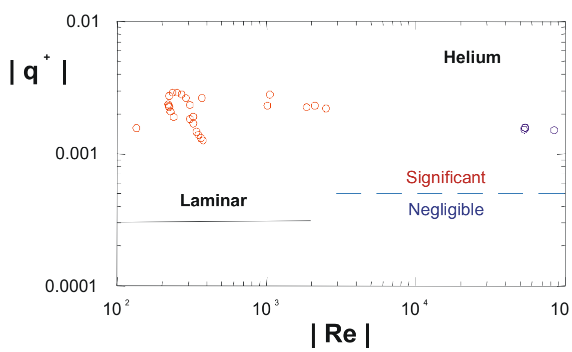

Fig. 3. Expected order-of-magnitude of non-dimensional heat flux during normal operating conditions and a hypothetical LOFA scenario in a helium-cooled GFR design.

ENDNOTES

* Partly supported by Generation IV Nuclear Energy Systems program as part of the Next Generation Nuclear Plant and Gas-cooled Fast Reactor efforts through DoE/NE Idaho Operations Office contract DE-AC07-99ID13727.

REFERENCES

Bankston, C. A., 1965. Fluid friction, heat transfer, turbulence and interchannel flow stability in the transition from turbulent to laminar flow in tubes. Sc.D. Thesis, U. New Mexico.

Black, D., I., G. E. Klinzing and I. W. Therney, 1977. Temperature-viscosity induced laminar instabilities in a gaseous heated channel. *Nuc. Engr. Design,* 40, pp. 225-233.

Hejzlar, P., W. C. Williams and M. J. Driscoll, 2004. Hot channel flow starvation of helium-cooled GFRs in laminar natural convection. *Trans., Amer. Nuclear Soc.,* 91, p. 202.

MacDonald, P. E., J. W. Sterbentz, R. L. Sant, P. D. Bayless, R. R. Schultz, H. D. Gougar, R. L. Moore, A. M. Ougouag and W. K. Terrry, 2003. NGNP preliminary Point Design -- Results of the initial neutronics and thermal-hydraulic assessments. Tech. report INEEL/EXT-03-00870 Rev. 1.

McEligot, D. M., and J. D. Jackson, 2004. "Deterioration" criteria for convective heat transfer in gas flow through non-circular ducts. *Nuc. Engr. Design,* 232, pp. 327-333.

McEligot, D. M., P. M. Magee and G. Leppert, 1965. Effect of large temperature gradients on convective heat transfer: The downstream region. *J. Heat Transfer*, 87, pp. 67-76.

McEligot, D. M., and G. E. McCreery, 2004. Scaling studies and conceptual experiment designs for NGNP CFD assessment. Tech. rpt. INEEL/EXT-04-02502.

Reshotko, E., 1967. An analysis of the laminar-instability problem in gas-cooled nuclear reactor passages. *AIAA J.*, 5, No. 9, pp. 1606-

Scheele, G. F., and T. J. Hanratty, 1962. Effect of natural convection on stability of flow in a vertical pipe. *J. Fluid Mech.*, 14, pp. 244-256.

Williams, W., P. Hejzlar, M. J. Driscoll, W-J. Lee and P. Saha, 2003. Analysis of a convection loop for GFR post-LOCA decay heat removal from a block-type core. Tech. report MIT-ANP-TR-095, Massachusetts Institute of Technology, March.