INL/CON-15-34330
PREPRINT

Experimental Study of Forced Convection Heat Transfer During Upward And Downward Flow of Helium at High Pressure and High Temperature

Proceedings of the 1st Thermal and Fluid Engineering Summer Conference, TFESC

Francisco I. Valentín
Narbeh Artoun
Masahiro Kawaji
Donald M. McEligot

August 2015

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

Proceedings of the 1st Thermal and Fluid Engineering Summer Conference, TFESC
August 9-12, 2015, New York City, USA

TFESC-12797

EXPERIMENTAL STUDY OF FORCED CONVECTION HEAT TRANSFER DURING UPWARD AND DOWNWARD FLOW OF HELIUM AT HIGH PRESSURE AND HIGH TEMPERATURE

Francisco I. Valentín[1], Narbeh Artoun[1], Masahiro Kawaji[1,2*], Donald M. McEligot[3]

[1]City College of New York, 160 Convent Ave, New York, NY 10031, USA
[2]The CUNY Energy Institute, 160 Convent Ave, New York, NY 10031, USA
[3]Idaho National Laboratory, 1955 N. Fremont Avenue, Idaho Falls, ID 83415-3560, USA

ABSTRACT

Fundamental high pressure/high temperature forced convection experiments have been conducted in support of the development of a Very High Temperature Reactor (VHTR) with a prismatic core. The experiments utilize a high temperature/high pressure gas flow test facility constructed for forced convection and natural circulation experiments. The test section has a single 16.8 mm ID flow channel in a 2.7 m long, 108 mm OD graphite column with four 2.3kW electric heater rods placed symmetrically around the flow channel. This experimental study presents the role of buoyancy forces in enhancing or reducing convection heat transfer for helium at high pressures up to 70 bar and high temperatures up to 873 ^{o}K. Wall temperatures have been compared among 10 cases covering the inlet *Re* numbers ranging from 500 to 3,000. Downward flows display higher and lower wall temperatures in the upstream and downstream regions, respectively, than the upward flow cases due to the influence of buoyancy forces. In the entrance region, convection heat transfer is reduced due to buoyancy leading to higher wall temperatures, while in the downstream region, buoyancy-induced mixing causes higher convection heat transfer and lower wall temperatures. However, their influences are reduced as the Reynolds number increases. This experimental study is of specific interest to VHTR design and validation of safety analysis codes.

KEY WORDS: forced convection, heat transfer, helium, VHTR, high temperature gas reactor, buoyancy effect

1. INTRODUCTION

The buoyancy effect is known to produce interesting phenomena in both laminar and turbulent flows. In laminar flows, buoyancy could effectively result in enhanced heat transfer, leading to mixed convection conditions. On the other hand, turbulent heat transfer could deteriorate due to fluid acceleration near the wall, which could in turn, modify normal turbulent velocity profiles and reduce turbulence generation (conditions previously described as flow laminarization).[1-3] The criterion for buoyancy driven flows is based on the buoyancy parameter, *Bo**, which after applying the Dittus-Boelter correlation for gases and the Blasius friction factor correlation, can be defined as: [4]

$$Bo^* = \frac{Gr^*}{\mathrm{Re}_{Dh}^{3.425}\,\mathrm{Pr}^{0.8}} \tag{1}$$

where the Grashof number, *Gr**, is defined in terms of the wall heat flux as:

$$Gr^* = \frac{g\beta q''_{wall} D_h^4}{k\nu^2} \tag{2}$$

This parameter is pertinent to turbulent flows. If *Bo** exceeds a certain critical value, differences could become evident between the upward and downward flow results under otherwise identical conditions. For the downward flow, the Nusselt number has been observed to be greater than that for the upward flow (the buoyancy-aided case).[4] According to previous experiments, if the buoyancy threshold is surpassed the effectiveness of heat transfer for downward flows is always enhanced in relation to that evaluated using the correlation for forced convection at the same value of the Reynolds number and core-to-bulk-temperature

*Corresponding Author: kawaji@me.ccny.cuny.edu

ratio. Accordingly, for values of $Bo^* <\sim 6x10^{-6}$, the upward and downward flow data should come together[5], due to the small buoyancy effect.

This paper provides a comparison between up-flow and down-flow forced convection data for helium at high pressure and temperature. The buoyancy effects are evaluated with regards to their effect on local heat transfer. This will be done by comparing the wall temperature profiles for upward and downward flows under similar experimental conditions (i.e., inlet temperature, heater power, pressure and flow rate).

2. EXPERIMENTAL SETUP

A high pressure/high temperature test facility has been constructed to obtain forced convection and natural circulation heat transfer data for helium and other gases, such as air and nitrogen, in a graphite flow channel. The cylindrical test section consists of five main layers. The outer layer would be composed of a stainless steel pressure vessel, which is ASME certified at 70 bar at 623°K. Between the graphite and the pressure vessel is a 25.4 mm (1”) thick fiber glass insulation layer, with a thermal conductivity which varies from 0.05 to 0.2 W/mK. The graphite test section is 2.7 m long with a 107.95 mm (4.25”) OD. It is made of graphite 348 with a thermal conductivity of 128 W/mK. Each graphite test section has 5 bore-through holes, four of which are for inserting electric heater rods symmetrically around a central flow channel. The four heater rods are 12.7 mm (0.5”) in OD and can produce heat up to 2.3 kW each. The central flow channel is 16.8 mm in diameter in which pressurized gas flows. A schematic of the gas flow loop constructed is shown in Fig. 1a. It has a gas circulation system based on a booster pump (as shown in Fig. 1b) which was added to provide a continuous gas flow in the closed loop.

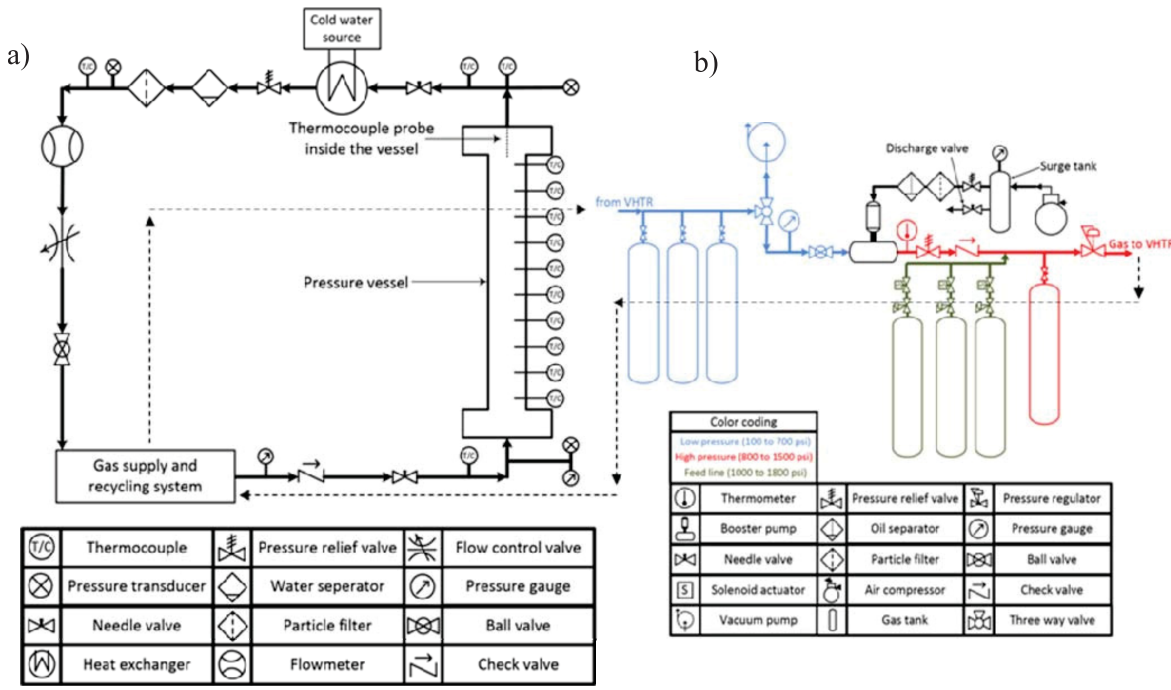

Fig. 1 (a) Schematic diagram of the High Pressure/High Temperature Gas Flow Loop, (b) Schematic diagram of the Gas Supply and Recycling System

EXPERIMENTAL PROCEDURE

Each experiment involved the independent selection and control of three parameters: graphite mid-point temperature, gas pressure and flow rate. While the graphite mid-point temperature was controlled by the heater power, pressure and flow rate were set by a pressure regulator and manually controlled valve, respectively. Experiments were begun by turning on the power for four electric heater rods. The heater power settings were individually controlled with AC variable transformers. The operating pressure was set and the manual flow control valve was opened to allow a very small flow rate (20-30 SLPM) and the booster pump operation began. The low gas flow rate was initially used so that the axial temperature profile in the graphite would reach close to the final temperature profiles more quickly. After the desired mid-point graphite temperature was achieved, the heater input power was adjusted, and the flow rate was set to the desired value. Data acquisition was continued until near steady state values were reached in all parameters. Steady state was declared when the change in any of the graphite temperatures was less than 3 K/hour. This quantity represents a total of 28W, which is less than 1% of the total power input by the heaters. The data were then analyzed for this specific time period.

4. DATA ANALYSIS METHODOLOGY

This section discusses the methodology involved in calculating flow heat transfer parameters from the obtained measurements. Having measured the mass flow rate through the system, it was possible to determine the local Reynolds number at any axial location, by knowing the local bulk temperature and using Eq. (3),

$$\mathrm{Re} = \frac{2\dot{m}}{\pi \mu r} \tag{3}$$

where the local dynamic viscosity μ, is evaluated at the local bulk temperature.[6] The bulk temperature profile of the gas was determined by dividing the graphite test section into 11 segments and carrying out an energy balance for each segment. The inlet and outlet bulk temperatures for each segment were then determined using Eq.4,

$$T_{i+1} = T_i + \frac{\Delta Q}{c_p \dot{m}} \tag{4}$$

where T_i and T_{i+1} denote the inlet and outlet bulk temperatures in each segment, and ΔQ is the heat removed by the gas with the specific heat capacity of C_p = 5,193 J/kg·K[6] flowing at a mass flow rate of $\dot{m}$. For Eq. (4), ΔQ was calculated per segment as follows,

$$\Delta Q = Q_{in} - Q_{out,tot} = \frac{\sum_{n=1}^{4} P_n}{11} - Q_{HL} - Q_{axial} \tag{5}$$

where Q_{in} for each segment was constant and equal to the sum of the heat generated, P_n, by four heater rods in each segment, and $Q_{out,tot}$ included heat loss from the PV surface and net axial conduction for each segment. The rate of heat loss from the PV surface, Q_{HL}, was correlated to the average value of the PV surface and the graphite temperatures at each elevation. This correlation was obtained from stagnant gas tests. A simple diagram of this methodology is illustrated in Fig. 2. By performing stagnant gas tests, one could correlate surface heat losses, and then apply this correlation to forced convection tests per segment as presented in Fig. 2b. The axial conduction term, Q_{axial}, was the sum of the net axial heat conduction in both the stainless steel PV wall and graphite test section, which could be obtained from the axial temperature gradients measured. The final unknown needed to perform the forced convection calculations to obtain the local heat transfer coefficient was the inner wall temperature of the graphite test section.

$$\Delta Q = h_{conv}(T_{wi}-T_i)A_i \tag{6}$$

Having measured the graphite temperatures at three different radial positions at any axial elevation, the radial temperature profile was extrapolated to obtain the inner wall temperature, T_{wi}, and calculate the heat transfer coefficient, h_{conv}.

5. RESULTS AND DISCUSSION

Downward and upward flow experiments were carried out for ten flow conditions. Fig. **3** compares the graphite wall temperatures for two of these runs. As can be observed in Fig. 3b, downward flows display higher and lower wall temperatures in the upstream and downstream regions, respectively, compared to the upward flow runs due to the influence of the buoyancy forces (high Bo^*). In the upstream region, convection heat transfer is reduced due to buoyancy leading to higher wall temperatures, while in the downstream region, buoyancy-induced mixing could cause higher convection heat transfer and lower wall temperatures (for downward flow). However, these effects are not evident at a higher inlet Reynolds number of 2,900 (lower Bo^* number) as shown in Fig. 3a. Down flow heat transfer is aided in the downstream section, while it is hindered for upflow. The reverse is observed in the upstream section. This effect is more pronounced as the buoyancy number increases. In all tests the buoyancy number decreases in the axial direction.

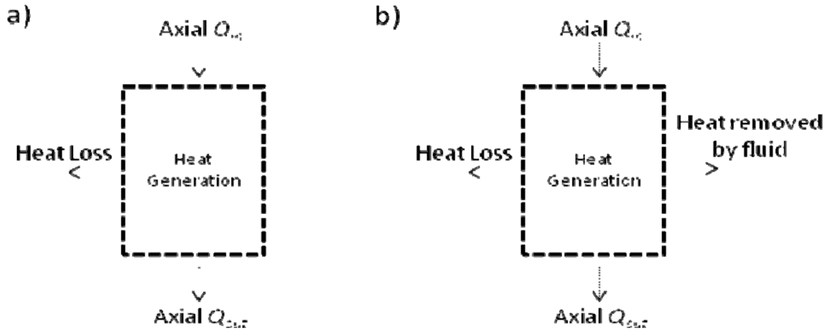

Fig. 2 Heat balance diagram for a) stagnant gas tests performed to quantify the test section's heat loss to the ambient, and b) forced convection tests.

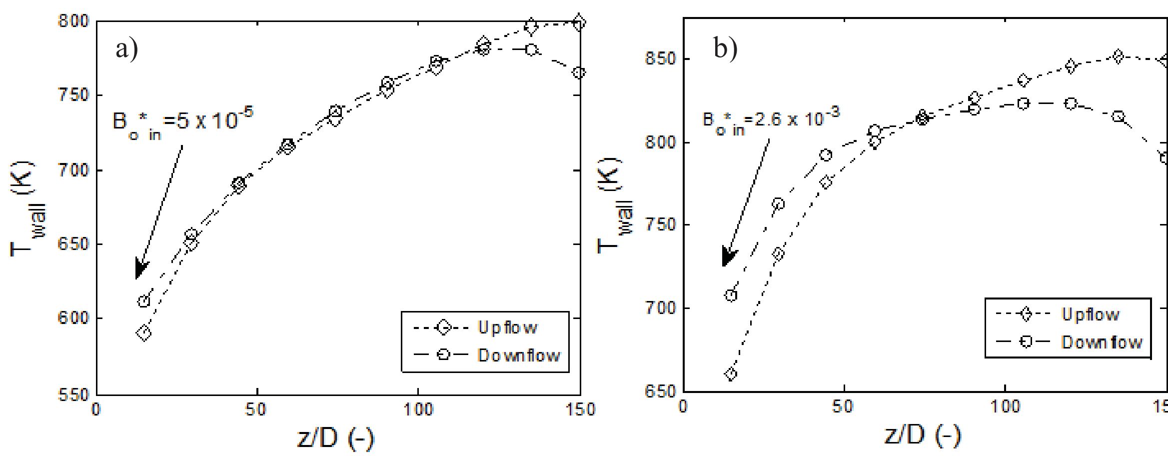

Fig. 3 Comparison of axial wall temperature profiles between upward and downward flows for a) low inlet *Bo** number, 500 psi, 275 SLPM, Re_{in}=2,900, and b) high inlet *Bo** number, 900 psi, 100 SLPM, Re_{in}=1,000.

6. CONCLUSIONS

This paper has compared upward and downward forced convection heat transfer results for helium from ten runs in order to evaluate the buoyancy effects on local heat transfer. The results provide evidences of enhanced heat transfer as the local heat transfer is enhanced by mixed convection, reducing the difference between the fluid and wall temperatures.

ACKNOWLEDGMENT

This research has been supported by a Contract No. 00119155 from the DOE Office of Nuclear Energy through the Nuclear Energy University Program.

REFERENCES

[1] Jackson, J.D., Hall, W.B., "Influences of buoyancy on heat transfer to fluids flowing in vertical tubes under turbulent conditions. In: Kakac, S., Spalding, D.B. (Eds), Turbulent forced convection in channels and bundles, 2. Hemisphere, pp. 613-640, (1979a).
[2] Li, J.K. Studies of buoyancy-influenced convection heat transfer to air in vertical tube. Ph.D. thesis. U. Manchester (1994).
[3] Lee, J. I., P. Hejzlar, P. Saha, M. S. Kazimi and D. M. McEligot, "Deteriorated turbulent heat transfer (DTHT) of gas up-flow in a circular tube: Experimental data" *Int. J. Heat Mass Transf.*, 51, pp. 3259-3266, (2008).
[4] McEligot, D. M., and J. D. Jackson, "Deterioration" criteria for convective heat transfer in gas flow through non-circular ducts. *Nuc. Engr. Design*, 232, pp. 327-333, (2004).
[5] Jackson, J.D., Cotton, M.A., Axcell, B.P., "Studies of mixed convection in vertical tubes", *Int. J., Heat Fluid Flow,*10, pp.2-15, (1989).
[6] Peterson, H., The Properties of Helium: Density, Specific Heats, Viscosity, and Thermal Conductivity at Pressures from 1 to 100 bars from Room Temperature to 1800 K, *Danish* Atomic Energy Commission Research Establishment Risö Report No. 224, (1970).