JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 17, No. 1, January–March 2003

Heat Transfer Behavior of Gaseous Mixtures Containing Helium and Argon or Nitrogen

F. W. Giacobbe*
Chicago Research Center/American Air Liquide, Inc., Countryside, Illinois 60525

The relative heat transfer behavior of pure helium, argon, and nitrogen, as well as selected binary gaseous mixtures containing helium and either argon or nitrogen, was studied experimentally by measuring the temperature increase that each of these gases, or gas mixtures, experienced as they were forced to flow through the bore side of a steam-heated copper "tube" at progressively increasing gas flow rates. The experimental results demonstrated that certain gaseous mixtures, and even some pure gases, under well-defined and specific operating conditions, are more efficient in selected heat transfer applications than pure helium alone. The cost savings that may be a result of diluting helium with another less expensive gas, and using that mixture in place of pure helium in certain gaseous heat exchange applications, can be significant. In addition, the use of more efficient gas mixtures in selected heat transfer applications can also result in more compact, and less costly, heat exchanger hardware.

Introduction

IT does not seem to be widely known that some gas mixtures, employed under certain operating conditions, are more efficient in forced convective heat transfer applications than the pure gaseous components employed under the same operating conditions. This is pretty surprising behavior but not entirely unrecognized. However, some of the theoretical predictions made in connection with this phenomenon may be misleading regarding all of the conditions that must be met to maximize improvements in the forced convective heat transfer behavior of gaseous mixtures over that of the pure components.

For example, purely theoretical considerations have been used in the past to show that heat transfer coefficients of gas mixtures consisting of light and heavy components (where the terms "light" and "heavy" refer to molecular weight) are greater for these mixtures (when they are undergoing laminar flow behavior) than they are for pure gases alone.[1] Other theoretical considerations, regarding relative heat transfer coefficients, lead to the same conclusion when these gas mixtures undergo turbulent flow behavior.[1–3] However, recent experimental studies within our laboratories, related to the heat transfer behavior of certain gaseous mixtures, indicate that these theoretical results are either false or true only under certain restricted conditions. Because this kind of behavior may have important practical applications, a comprehensive experimental research study was undertaken in our laboratories to develop a better understanding of this phenomenon and to determine experimentally what operating conditions must be employed to optimize forced convective heat transfer behavior within smooth bore tube-in-shell heat exchangers when specific binary gaseous mixtures consisting of helium and argon or helium and nitrogen are passed through the tubes.

Helium was chosen as one of the gases for use in this research study because it is a relatively rare and expensive gas. Thus it is potentially advantageous to find ways to dilute helium with other gases if the resulting mixture can be used more efficiently in some type of heat transfer application that would normally employ only pure helium. Helium also has a very low molecular weight and, thus, has one of the highest static thermal conductivities of all of the common gases. Only hydrogen is somewhat better. Helium is also a monatomic noble gas. Therefore, thermally induced complications related to molecular structure, for example, interatomic vibration, rotation, or dissociation, are absent in this gas.

Argon was chosen as a gaseous component to be added to helium to make binary mixtures of these two gases because it is inexpensive, relative to helium. Thus, argon is a good choice as a diluent to add to helium if the mixture can be used more efficiently in any heat transfer application that would normally employ pure helium alone. Argon is also a simple monatomic gas. Therefore, thermally induced complications related to molecular structure are also absent in argon. In addition, argon has a relatively high molecular weight, with respect to helium, and, thus, has a relatively low static thermal conductivity, relative to helium. In addition, certain theoretical considerations consistently predict that improvements in forced convective heat transfer behavior tend to be more pronounced in binary gaseous mixtures containing very light and very heavy gases.

Nitrogen was chosen as another component to be added to helium to make additional binary gaseous mixtures for use in this experimental study. Mixtures of helium and nitrogen have many of the same advantages as mixtures of helium and argon. Thus, nitrogen is also a good choice as a diluent to add to helium if the mixture can be used more efficiently in any heat transfer application that would normally employ pure helium alone. It was also thought that the use of mixtures consisting of helium and nitrogen would provide interesting additional data that could be compared with corresponding data obtained using the helium/argon mixtures. However, nitrogen is not a simple monatomic gas. Therefore, thermally induced complications related to molecular structure are not absent in nitrogen. However, the temperature parameters employed during this study were deemed to be low enough to avoid significant complications related to the molecular structure of nitrogen.

General Description of Experimental Process

A general outline of the experimental method selected to help determine optimum heat transfer operating conditions that may be employed to maximize the forced convective heat transfer behavior between the inside surface of a hot tube and specific binary gaseous mixtures flowing through the tube follows.

Each of the pure gases, and then selected binary gas mixtures, was serially directed through a calibrated flow meter at a constant flow rate, then through a length of coiled tubing (submerged within an ice bath), then through a relatively short length of straight stainless steel (SS) tubing (also cooled to ice bath temperatures), then through the bore of a round hole drilled and reamed through a long (initially solid) copper cylinder. The outer section of this machined copper cylinder was heated uniformly and maintained at, or

---

Received 24 May 2002; revision received 16 September 2002; accepted for publication 17 September 2002.

*Senior Scientist, 5230 South East Avenue.

nearly at, 100°C, using live steam. After leaving the hole drilled through the machined copper cylinder, the gases passed through another relatively short straight section of SS tubing into the ambient atmosphere.

The temperature of the pure gas or gas mixture was measured just as it entered, and also just as it left, the hole drilled through the heated copper cylinder. The temperature change experienced by the gas in passing through the heated section of copper, as a function of volumetric gas flow rate, could then be used to compare the relative heat transfer behavior of the pure gases or gas mixtures as a function of the overall gas flow rate.

Precooling of the flowing gases, before their injection through the heated copper cylinder, ensured that each pure gas or gas mixture entered that section of the apparatus at nearly the same initial temperature. The overall length of the hole drilled through the heated copper cylinder was deliberately selected to ensure that the maximum outlet temperature of the gas stream would be well below the maximum possible outlet temperature of about 100°C for all possible gas flow rates actually tested. If this condition were not met, it would have been difficult to make any kind of valid comparisons of the relative heat transfer behavior of the gases tested.

A general schematic of the overall system and apparatus employed during this experimental study may be seen in Figs. 1 and 2.

Specific Experimental Components and Methods of Operation

Gas Flow Rate Measurements

The gas flow meter used during this study was a Fisher Porter Rotometer (Model FP-1/2-17-G10) with a 25.4-cm (10-in.) indicating scale marked between 0 and 100% of full scale. The smallest marked scale divisions indicated differences in gas flow rates as low as 1.0% of full scale. This flow meter was calibrated with air at 101.3 kPa (1.0 atm) and at 21.1°C. With the indicating float at the 100% mark, and with clean dry air at 101.3 kPa and at 21.1°C, the calibrated airflow was 54.37 l/min (115.2 standard ft^3/h).

All flow meter readings had to be corrected for the particular types of pure gases and gas mixtures that were actually employed (using the air calibrated flow meter just described), as well as for all other operating parameters that differed from those employed during the original calibration procedure. These corrections involved accounting for an indirect scale (in percent of true flow) vs true flow values, the density differences between the pure gases or gas mixtures and air, the actual gas pressures (within the flow meter) during gas flow rate measurements, and the actual flowing gas temperatures (within the flow meter) that existed during each gas flow rate measurement.[4,5]

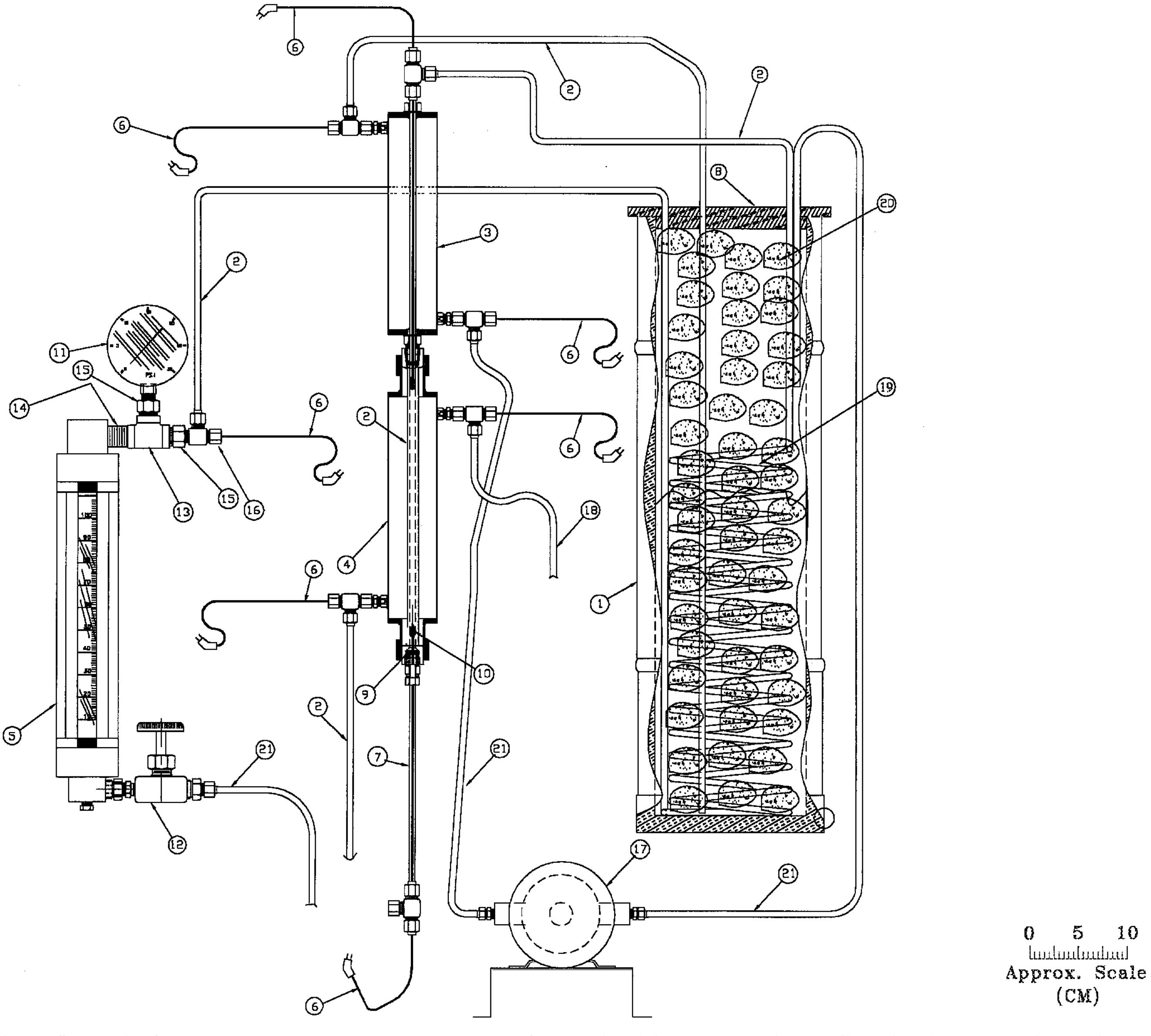

Fig. 1 **Schematic of apparatus used to measure gaseous heat transfer behavior: 1, insulated container; 2, Cu tubing; 3, cold water jacket; 4, steam jacket; 5, flowmeter; 6, TC probe; 7, SS tubing; 8, cork cover; 9, Teflon® sleeve; 10, TC centering tab; 11, pressure gauge; 12, needle valve; 13, SS tee; 14, SS pipe nipple; 15, reducing bushing; 16, TC adapter; 17, ice water pump; 18, rubbing tubing; 19, water level; 20, ice cubes; and 21, PE tubing.**

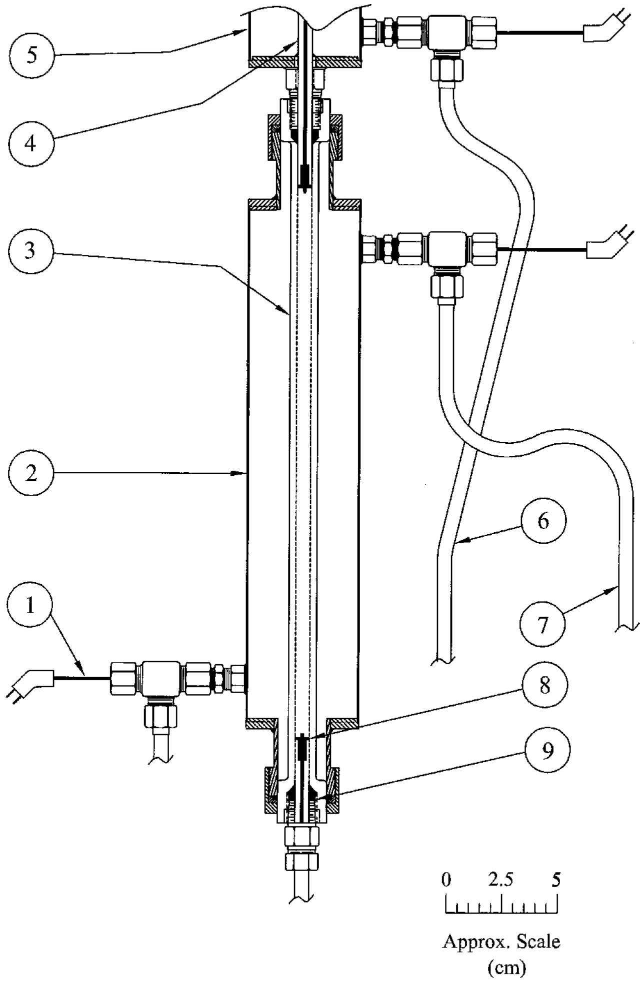

Fig. 2 Detailed view of steam heated section of heat transfer apparatus: 1, TC probe; 2, steam jacket; 3, Cu tube; 4, SS tubing; 5, cold water jacket; 6, PE tubing; 7, rubber tubing; 8, TC centering tab; and 9, Teflon sleeve.

Gas flow rates were controlled by means of high-pressure regulators located at each high-pressure cylinder (containing a pure test gas or preblended binary gas mixture) and a 0.635-cm (1/4-in.) National Pipe Tapered (NPT) needle valve (Parker, Inc., Model 4F-V6LR-B) threaded into a 1.27-cm (1/2-in.) NPT bushing connected into the base of the flow meter.

Pressures within the flow meter were measured using a precision pressure gauge (U.S. Gauge, Inc.) calibrated between 0 and 308 kPa absolute (0 and 30 psig). This gauge was located at the top (outlet) end of the flow meter. The gases flowing through the heated section of the copper cylinder were so close to the gas exhaust port, leading into the ambient atmosphere, that these gas pressures were all taken to equal about 101.3 kPa, no matter what the gas flow was. However, upstream gas pressures (within the flow meter itself and within the upstream tubing sections) were sometimes substantially higher than 101.3 kPa (especially at the highest gas flow rates) because of the overall tubing length that preceded the heated section of the machined copper cylinder.

Temperatures within the gas stream, exiting the flow meter, were measured by means of a 1.59-mm- (1/16-in.-) o.d. SS sheath, K-type, thermocouple (TC) inserted directly into the gas stream exiting the top end of the flow meter.

During each test trial, involving the separate pure gases or gas mixtures, gas flow rates were initially set as near as possible to the 100% of full-scale mark on the flow meter just after a barometric pressure/temperature reading was taken using a Fortin barometer. A sufficient period of time (usually a few minutes) was then allowed to pass until all temperature indicators stopped fluctuating. Then, all of the flow, temperature, and gauge pressure data related to that particular test trial was actually recorded. Also, if the initial target flows setting changed during the equilibration process, that new value was recorded rather than the value that was initially set. After completion of this process, a new lower flow rate was selected (usually about 10% of full scale lower than the initial target value), and the entire process was repeated. These steps were sequentially repeated until the recorded flow rates reached about 10% of the full-scale flow meter reading. When this sequence of steps was completed, the entire process was repeated once again, but the initial target flow setting chosen was at about 95% of the full-scale mark on the flow meter. In this way, approximately 18 final flow rate readings were obtained that were evenly (roughly) divided over the entire range of the full-scale flow that was possible with each gas tested.

After correcting all of the flow meter readings, the overall errors in the corrected readings were estimated to be at least ±2.0% of the full-scale reading (for each gas or gas mixture tested). However, separate gravimetric flow meter calibrations, using pure helium and then pure argon in this flow meter, indicated that corrected flow meter readings were actually within ±0.2% of the true gas flow rates when full-scale readings were taken using this instrument.

Gas Cooling/Conditioning

The gas stream exiting the gas flow meter was passed through a length of about 6.1 m of 0.635-cm- (20 ft of 1/4-in.-) i.d. copper tubing coiled within a vertical insulated SS container [about 7.57-liter (2.0-gal) capacity] filled with ice and water before it was directed through subsequent parts of the experimental apparatus.

After they left the ice bath, the gases were then passed through a short straight section of 0.704-cm-i.d. SS tubing (0.375 o.d. × 0.277 in. i.d.) that was cooled with ice water (pumped through a chamber surrounding the outside surface of that tube). This straight section of tubing was employed to retard a premature onset of turbulence within the gas before its introduction into the lower heated section of tubing. The i.d. of this SS section of tubing was deliberately chosen to be a little bit larger than the hole drilled through the copper cylinder immediately following the SS tubing. This design feature permitted the coaxial insertion of a temperature measuring TC probe throughout the entire length of the SS tube without causing a significant reduction in the cross-sectional annulus area within that tube. Therefore, as gases passed through this section of the apparatus (containing the axial TC probe) and then on into the next section (through the drilled hole in the heated copper cylinder, which only contained axial TC sensing junctions at the hole inlet and outlet points), there was no appreciable increase in gas velocity due to an appreciably smaller cross-sectional area associated with the hole in the copper cylinder.

Cooling of this straight section of SS tubing was also used to minimize preheating of the gas before its injection into the hole drilled through the lower heated section of the copper cylinder. This procedure helped to ensure that each gas or gas mixture tested would enter the heated copper cylinder at nearly the same temperature. Therefore, the overall heat transfer behavior between the heated copper cylinder and each gas or gas mixture would be influenced more by the specific nature of each gas or gas mixture rather than by significant differences in the inlet gas temperature.

Temperature Measurements

All temperature measurements were made using 1.59-mm- (1/16-in.-) o.d. SS sheath, K-type, TCs along with digital TC indicators (Omega Engineering, Model CNI16) capable of producing readouts to the nearest ±0.1°C. However, the error in individual temperature measurements was estimated to be on the order of ±0.2°C. In any case, the most critical temperature measurements, made during the course of this study, were related to determining the temperature increases that occurred in the pure gases and gas mixtures that passed through the heated copper cylinder. It was also understood that the propagation of systematic errors associated with subtracting one temperature from another (to find a temperature increase) was likely to have the most significant influence on errors in the resultant temperature increase values. Calibrating the cold gas inlet and hot gas outlet TCs during a separate experimental procedure minimized this kind of experimental error. A small correction (based on that calibration procedure) was then applied to all temperature differences that were subsequently obtained using these TCs. All temperature differences actually calculated, and then corrected in this way, were deemed to be in error by at least ±0.4°C.

The TCs employed to measure gas temperature increases were positioned so that each of their sensing junctions were very near (and inside) the opposite ends of the hole drilled through the steam-heated copper cylinder [6.35 ± 0.01 mm i.d. (about 1/4 in. i.d.)]. The exact distance between these TC sensing junctions (at the very end of each TC) was measured indirectly. This distance was 23.90 ± 0.05 cm (9.41 ± 0.02 in.) in length. These TCs were also inserted coaxially into their respective positions (and, thus, centered) within the gas inlet and outlet points located very near the opposite ends of the hole drilled through the copper cylinder. A very small metal positioning tab was attached near the sensing junction ends of each of these TCs to ensure that the end of each TC would remain in its respective centered position. The use of these centering tabs was necessary because each of the TCs that the tabs were attached to were relatively long. Therefore, this length factor made direct TC contact (at or near the temperature sensing junction) with the inside wall of the heated copper cylinder very probable but also very undesirable. Thus, the need for the TC centering tabs. However, an advantageous feature of this approach was that both of these TCs could be inserted coaxially within the relatively long straight sections of tubing that preceded and followed the heated section of the copper cylinder. Thus, severe obstructive interference with the flowing gas streams (that might have been caused by perpendicular insertion of the TC probes) was avoided, and the premature onset of turbulence, within the flowing gas streams, could be retarded but not eliminated. This unavoidable feature of the experimental apparatus probably did accelerate the onset of turbulence to some degree. This will be discussed again and in more detail subsequently. In any case, both of the TC centering tabs were very small in size and mass and also positioned far enough away from the actual sensor junctions to avoid systematic temperature readout errors due to thermal conduction through the centering tabs. The measurement of flowing gas temperatures (especially at high gas flow rates) also tended to minimize this kind of systematic temperature readout error.

Additional TC positioning and other fabrication details, related to gas temperature measurements within the heated copper cylinder, may be seen in Fig. 2. Although all of the design features indicated in Fig. 2 were not perfect (from the point of view that something was in the gas stream that could have had some influence on the transition between laminar and turbulent gas flow), they did allow a reasonable tradeoff between building a practical and useful experimental device vs a more perfect but impractical one.

Steam Generator

The steam needed to hold the temperature of the heated copper cylinder near 100°C was generated within a standard pressure cooker heated using an electric hot plate. A thick-walled section of rubber vacuum tubing conducted the steam between the pressure cooker and the SS shell surrounding the heated copper cylinder. The actual steam temperature entering and leaving this SS shell was directly measured using additional TCs attached to two separate digital readout meters. All steam temperatures measured in this way were always at or above 99°C (at both the inlet and outlet connections in the SS shell). Because atmospheric pressure readings within our laboratory were always a little less than 101.3 kPa, it was reasonable to see steam temperatures at slightly less than 100°C.

The experimentally measured steam production rate of this part of the system was about 0.265 g/s. This steam production rate was sufficient to keep the steam-heated copper cylinder at (or nearly at) 100°C at all gas flow rates tested during the course of this experimental study. Approximately 32.2% of the total electrical power consumed (during the steam-generation process) was lost by radiation, convection, and conduction into the ambient air surrounding the electric hot plate and pressure cooker.

Condensation of steam, at a flow rate of 0.265 g/s, was capable of delivering heat (through the copper cylinder wall) at a rate no greater than 598 W. Pure helium, moving at a maximum flow rate of about 240 l/min, and also heated from 0 to about 45°C, requires a heat input of about 155 W to produce this temperature increase. Therefore, the steam production rate, noted earlier, was adequate to supply this maximum heat energy requirement (not only for helium but for pure argon and nitrogen, as well as for all of the gas mixtures tested during this study) and to still keep the hot copper cylinder at, or very near, 100°C throughout the entire range of gas flows actually maintained during this experimental study. It is also understood that the temperature of the inner surface of the hole drilled through the heated copper cylinder had to be slightly lower than the temperature of the outer (steam-heated) surface to enable heat transport through the cylinder wall and into the flowing gas streams. However, for all practical purposes, this temperature difference could be neglected (at all of the gas flow rates actually tested) because of the very high coefficient of thermal conductivity of copper.

Gases and Specific Gas Mixtures

All pure gases and gas mixtures used during this study were obtained from the Air Liquide LaPorte Cylinder Filling Plant. The pure gases were all “high purity” grade. All of the gas mixtures were prepared and certified by weight using one or more scales certified against standard weights traceable to National Institute of Standards and Technology number 882/254480. By the use of this technique it was possible to certify gas mixture concentrations to the nearest ±0.01 mole%. However, all subsequently mentioned percentage mixture compositions of helium/argon or helium/nitrogen refer to percentage composition by volume or mole percent of the individual gaseous components. In addition, all of the pure gases and gas mixtures were employed, as delivered, in high-pressure gas cylinders. The helium was in size 49 cylinders; all other gases and gas mixtures were delivered in size 44 cylinders.

Results and Discussion

Graphical Results

The primary experimental results of this study may be seen in Figs. 3 and 4. Figure 3 summarizes the temperature-related heat transfer effects that were produced when pure helium, pure argon, and several binary mixtures consisting of helium and argon were directed through the hole drilled through the uniformly heated copper cylinder. Figure 4 summarizes the temperature-related heat transfer effects that were produced when pure helium, pure nitrogen, and several binary mixtures consisting of helium and nitrogen were directed through the same hole drilled through the heated copper cylinder. As already mentioned, this heated section of the copper cylinder had an i.d. of 6.35 mm (about 1/4 in.) and a length of 23.9 cm (about 9.41 in.). This length measurement represents the distance between the gas inlet and outlet temperature measuring TC junctions. The actual drilled-out hole length was a little bit longer.

The most significant behavior illustrated in Figs. 3 and 4 is the temperature increase that each gas or gas mixture experienced (in passing through the heated copper cylinder) as a function of gas flow rate. All of the gas flow rates indicated in these graphs have been expressed in liters per minute (at 101.3 kPa and 21.1°C).

Initially, at very low gas flow rates (and low gas velocities), when all pure gases or gas mixtures were undergoing laminar flow, pure helium outperformed all mixtures of helium/argon and helium/nitrogen (as well as pure argon or pure nitrogen) as a gaseous heat transfer agent. This is illustrated clearly in Figs. 3 and 4 because pure helium exhibited the highest gas temperature increase over all other gas mixtures (tested under the same operating conditions) that it was compared to at very low overall gas flow rates. In addition, the order of this “efficiency” in heat transfer performance (only at very low gas flow rates) goes from pure helium (the best) to pure argon or pure nitrogen (the worst), with all intermediate compositions performing between helium/argon and helium/nitrogen (with gas mixtures containing more helium always performing better than those containing less helium).

With reference to Figs. 3 and 4, it can be seen that, although the temperature increase of the pure helium (as well as the other

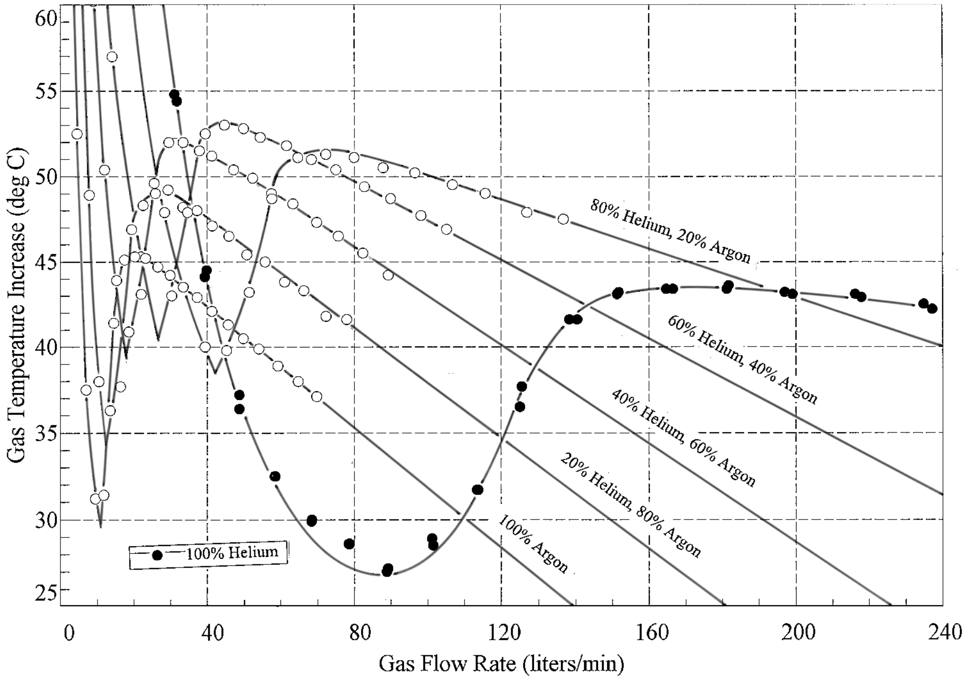

Fig. 3 Heat transfer behavior of helium, argon, and binary mixtures of helium and argon.

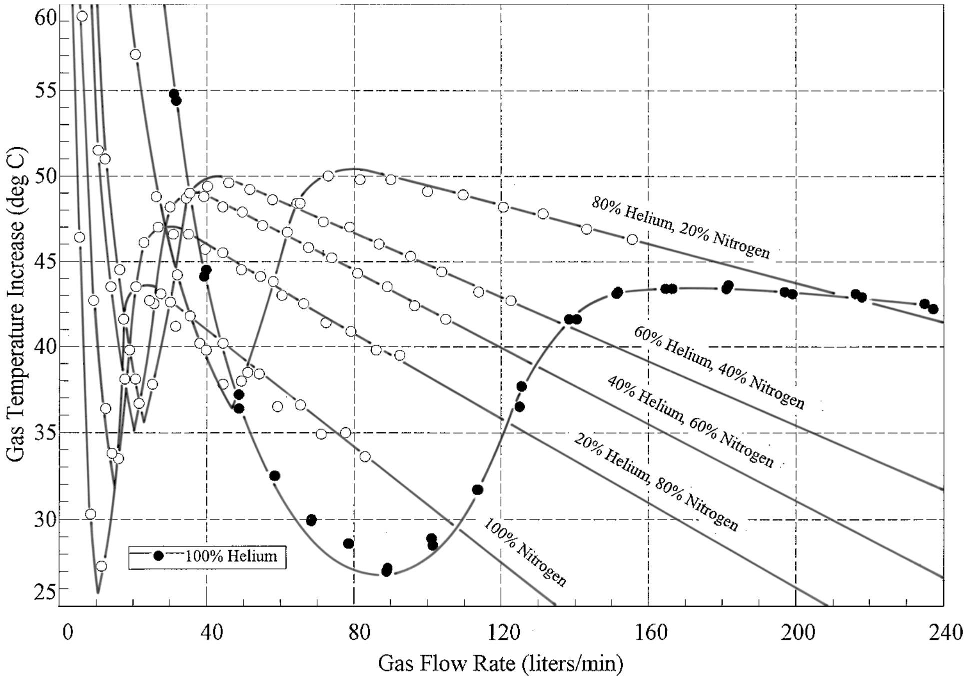

Fig. 4 Heat transfer behavior of helium, nitrogen, and binary mixtures of helium and nitrogen.

gases tested) was relatively high at very low gas flow rates, these temperature increases dropped off very rapidly at higher and higher gas flow rates. This behavior at relatively low flow rates makes sense because more gas flows through the heated copper cylinder per unit time at higher flow rates. Thus, temperature increases should drop off somewhat with higher and higher gas flow rates because a greater mass of gas must be heated (per unit time) at the higher gas flow rates. However, when helium gas flow rates reach about 90 l/min, the gas temperature change stops decreasing and begins to increase from a minimum of about 27°C to a maximum of about 44°C, and then it more slowly begins to decrease again with further increases in the helium gas flow rate. This may seem a little odd until one considers that the pure helium undergoes transitional flow behavior between essentially laminar flow and fully turbulent flow in the region between about 60 and 170 l/min within this system. Therefore, the transfer of heat between the tube walls and the gas begins to improve significantly in the vicinity of 90 l/min all the way up to about 170 l/min. Above a flow rate of 170 l/min, the gas flow is fully turbulent and no further improvement in heat transfer can occur between the tube wall and the flowing gas. Thus, further increases in the gas flow rate, from that point and onward, tend to diminish the observed temperature increases because a greater mass of gas must be heated per unit time and there is no corresponding improvement in the heat transfer behavior between the inside surface of the hole drilled through the heated copper cylinder and the gas passing through.

If the presence of the TC and TC centering tab (near the entrance of the hole drilled through the heated copper cylinder) did hasten the onset of the transition between laminar and turbulent flow behavior, the position of the "troughs" in Figs. 3 and 4 are probably located at gas flow rates that are a little less than the one that would have been obtained if those obstructions had not been present. However, presumably, all of the pure gases and gas mixtures would have been affected similarly, and so all of the troughs would tend to move in the same direction, that is, toward higher gas flow rates, and one would see similar relative behavior.

Expectations at Very High Gas Flow Rates

At extremely high gas flow rates, the helium gas temperature increases (as well as all of the gas temperature increases for mixtures of helium/argon and helium/nitrogen) should asymptotically approach zero. This may not be obvious from the graphs in Figs. 3 and 4 because the graph abscissas do not extend beyond flows of 240 l/min. This graphical limit was employed because the most interesting heat transfer behavior, exhibited by all of the gases tested, occurred at lower flow rates. In any case, the helium curves tend to illustrate neatly the kind of heat transfer behavior that one can expect due to the transition of gas flow rates between laminar and turbulent flow regimes occurring within a cylindrical tube. All pure gases can be expected to exhibit similar behavior except for the positions and magnitudes of the temperature increases that will occur between the laminar and fully turbulent flow regimes.

The main point here is that even though the extrapolated lines in Figs. 3 and 4 all appear to be relatively straight, they must all asymptotically approach a delta T (where delta T means the temperature increase experienced by any pure gas or gas mixture as it passed through the hole drilled through the steam heated copper cylinder) of zero at extremely high gas flow rates. Their order in approaching this condition (considering now only Fig. 3) will be from pure argon (tending to approach this condition at the lowest flow rates), then gas mixtures containing very little helium, up to pure helium (tending to approach this condition at, respectively, higher and higher flow rates). Approaching a delta T condition of zero does not mean that the gas in question stops carrying heat out of the system; it just means that a lot more gas is used to transport the heat that is carried out of the system. For example, if pure helium flowing at 1000 l/min leaves a heated tube (maintained at a constant temperature) after experiencing a temperature increase of 10°C, a certain quantity of heat will have been carried away within the helium. However, if the pure helium flow is then increased to 10,000 l/min, but the temperature increase experienced by the helium is only 1.0°C, the same quantity of heat will be carried away within the helium but 10 times as much helium (within the same time period) will have been used to accomplish this effect. The point is that the use of higher and higher gas flow rates will not necessarily transfer heat into or away from something else any faster than lower gas flow rates when one is only comparing a specific gas or gas mixture against itself with respect to varying gas flow rates. However this kind of effect, for a specific gas or gas mixture, will only be significant when that gas or gas mixture is undergoing either purely laminar or purely turbulent flow behavior because, in these cases, there is a progressive drop in temperature as gas flow rates increase.

Laminar/Turbulent Flow Behavior/Heat Convection Mode

When the helium/argon and helium/nitrogen gas mixtures, tested within the same system (under practically identical conditions) are considered in greater detail, it is evident that, within certain restricted ranges of flow rates, all of the gas mixtures (and even pure argon alone) were capable of performing as good as (or better than) pure helium alone as heat transfer agents. These interesting results are a function of gas flow rate (or gas velocity) as well as gas mixture composition because these parameters are critical determining factors of where the transition between laminar and turbulent flow will occur for any gas. It also can be seen that the heavier gases or gas mixtures that reach the turbulent flow regime, typically at much lower flow rates than pure helium, are capable of acting as better heat transfer agents than pure helium within a restricted range of flow rate conditions. However, as flow rates continue to increase and all of the gases or gas mixtures reach fully developed turbulent flow, helium again becomes the best gaseous heat transfer agent. These same comments apply equally as well to the helium/nitrogen system.

Table 1 Estimated Reynolds numbers of pure gases and gas mixtures at fully turbulent flow condition

Gas or gas mixture	Average gas temperature, °C	Flow rate, l/min	Reynolds number
He	21	170	4500
Ar	20	20	5000
N2	19	20	4400
He/Ar, 80/20	23	70	4900
He/N2, 80/20	23	75	5300

In addition to some of the preceding comments note that the heat convection mode into a flowing gas stream also changes with gas flow rate. For example, at very low gas flow rates, heat transfer effects are dominated by the natural convection mode, and the effects of buoyancy are important in the range of very low gas flow rates, which is evident from the large temperatures increases experienced by all of the gases and gas mixtures at very low gas flow rates. As the gas flow rates increase, the dominant convection mode changes from natural convection to mixed convection (combined natural and forced convection) and then to forced convection. The curves plotted in Figs. 3 and 4 provide graphic illustrations of this behavior.

To further amplify some of these comments and conclusions, estimates of the actual Reynolds numbers that were associated with fully turbulent flow behavior in pure helium, argon, nitrogen, and some of the gas mixtures tested during this study have been calculated and listed in Table 1. This calculation process involved estimating the actual gas flow of each gas, or gas mixture that was associated with fully turbulent flow behavior from Fig. 3 or 4 and then calculating the Reynolds number using that information as well as additional information related to that particular case. In each case treated in this way, fully turbulent flow behavior for any pure gas or gas mixture was assumed to exist at the flow that was associated with the highest delta T value that immediately followed the trough region of each plotted curve. For pure helium, this condition tended to occur at a flow rate of about 170 l/min. For the 80% helium/20% argon mixture, this condition tended to occur at about 70 l/min. Average temperatures also had to be estimated for each gas or gas mixture. These temperatures were then used to estimate average gas densities and gas viscosities for use in the Reynolds number calculations. Because of the uncertainties in these estimated parameters, all subsequently calculated Reynolds numbers were rounded off to only two significant figures and have been listed (along with the estimated primary parameters) in Table 1. See Refs. 6 and 7 or other similar references for details concerning Reynolds number calculations. Initial gas temperature and pressure are about 0°C and 101.3 kPa. Gas densities were calculated using average gas temperatures and average molecular weights. Pure gas viscosities were calculated using average gas temperatures and data from Ref. 8. The helium/argon gas mixture viscosity was estimated using average gas temperatures and information in Refs. 9 and 10. The helium/nitrogen gas mixture viscosity was estimated to be approximately equal to that of pure nitrogen at 23°C (Ref. 11).

Note that all of the calculated Reynolds numbers (Table 1) range between about 4400 and 5300. Typically, for liquids, fully turbulent flow behavior is achieved when Reynolds numbers reach or exceed 3000 (Ref. 6). However, for fluids in general (gases and liquids), other sources[7] indicate that a Reynolds number of 2300 represents the upper limit for laminar "pipe" flow and that fully turbulent flow occurs in the range of Reynolds numbers between about 5000 and 10,000. Other authorities[12] point out that it is possible to maintain purely laminar flow at very high Reynolds numbers if care is taken to increase the fluid flow very gradually. However the slightest disturbance, for example, an onset of vibration, will destroy the laminar flow conditions if the Reynolds number exceeds 4000. Alternatively, if the fluid flow is initially turbulent, this condition can be maintained at very low Reynolds numbers unless some disturbance occurs when a Reynolds number is less than 2000. As a result, pipe flow involving a fluid having a Reynolds number between about 2000 and 4000 is generally referred to as unstable. All of these comments are consistent with the experimental results summarized here in Figs. 3 and 4 and in Table 1.

Heat Capacity Related Comments

The shapes of the curves illustrated in Figs. 3 and 4, especially with regard to the measured delta T values, can be significantly influenced by the molar heat capacity of the gases that might be tested as described within this paper. In other words, unless all pure gases and gas mixtures have identical molar (or volumetric) heat capacities, one cannot arbitrarily compare different curves of this type, at fixed volumetric flow rates, to determine which gas or gas mixture is "better than" another with respect to heat transfer behavior. For example, if one flowing gas (or gas mixture) stream has a molar heat capacity that is twice that of another gas, but both are heated from the same initial temperature to the same final temperature, the gas with the higher heat capacity will carry away twice as much heat as the gas with the lower heat capacity.

In cases involving helium, argon, and helium/argon mixtures (as in Fig. 3), the molar heat capacity of helium, argon, and all possible mixtures of these gases is constant [at about 20.79 J/(mol deg), near room temperatures]. Therefore the ratio of the measured delta T values for any combination of these two pure gases, or any combination of one pure gas and one mixture of the two gases (flowing at a specific and constant rate in the vicinity of room temperatures), will be equal to the relative heat transfer capacity of that particular combination of gases. For example, consider the behavior of pure helium vs a mixture of 60% helium/40% argon, as shown in Fig. 3 at a constant flow rate of 80 l/min. Under the conditions that prevailed when those data were collected, the pure helium experienced a delta T value of about 27°C, but the mixture of helium and argon experienced a delta T value of about 50°C. The numerical ratio of 50/27, that is, 1.85, indicates that the gas mixture was about 1.85 times as effective as the pure helium in removing heat from the heated copper cylinder. No corrections for differing molar heat capacities are needed in this case.

In cases involving helium, nitrogen, and helium/nitrogen mixtures (as in Fig. 4), the molar heat capacity of helium is, as indicated in the preceding paragraph, 20.79 J/(mol deg), but the molar heat capacity of nitrogen is about 29.12 J/(mol deg). All possible mixtures of helium and nitrogen will have average molar heat capacities that will vary between these two values. Thus, the ratio of the measured delta T values for any combination of these two pure gases, or any combination of one pure gas and one mixture of the two gases (flowing at a specific and constant rate in the vicinity of room temperatures), will not equal the relative heat transfer capability of that particular combination of gases. For example, consider the behavior of pure helium vs a mixture of 60% helium/40% nitrogen, as shown in Fig. 4 at a constant flow rate of 80 l/min. Under the conditions that prevailed when those data were collected, the pure helium experienced a delta T value of about 27°C, but the mixture of helium and nitrogen experienced a delta T value of about 47°C. The numerical ratio here is about 47/27, that is, about 1.74, but the heat capacity of the mixture was about

$$[0.60(20.79) + 0.40(29.12)] = 24.12 \text{ J/(mol deg)} \qquad (1)$$

Thus, the mixture's heat capacity was about 24.12/20.79, or about 1.16 times greater than the heat capacity of pure helium. Therefore, if the same volume of this gas mixture containing nitrogen were heated through the same delta T as an equal volume of pure helium, the gas mixture would absorb about 1.16 times more heat than the pure helium. The point is that these considerations must be made in comparing the heat carrying capacity of any combination of pure gases and gas mixtures if the individual gases have differing molar heat capacities. These kinds of considerations could have been taken into account before plotting the graph in Fig. 4 so that relative heat transfer capabilities could have been found more directly from a slightly modified graphical plot. However, it was thought that plotting the original data would be more straightforward and less likely to lead to other errors in interpretation.

Summary of Results

Figures 3 and 4 summarize the temperature-related heat transfer effects that were produced when pure helium, argon, nitrogen, and several binary mixtures consisting of helium/argon and helium/nitrogen were directed through a hole drilled through the axis of a heated copper cylinder (as described earlier and shown in Fig. 2). All of the experimental results related to the helium/argon gas mixtures were very similar to the findings obtained with the binary mixtures of helium/nitrogen. Elaborations regarding this behavior are contained in the preceding text. A comparison of the results summarized in Figs. 3 and 4 also indicates that these findings are probably not unique and are likely to be similar to the results that one would obtain for all mixtures of heavy and light gases employed under the same set of operating conditions. However, one would expect to see slight differences, at least, between the "windows of opportunity" and the magnitudes of the temperature differences that may exist between pure gases and binary gas mixtures, at specific volumetric gas flow rates or gas flow velocities.

Furthermore, at very low and very high flow rate conditions, pure helium was the best gaseous heat transfer agent that was tested during this study. However, at intermediate flow rates, that is, at gas flow velocities in the vicinity of the laminar to turbulent transitional region for pure helium, certain light/heavy gas mixtures (and even certain heavy pure gases, such as argon) are capable of outperforming pure helium as heat transfer agents. Additional experimental data, obtained by similarly testing other heavy/light gas mixtures, has confirmed this general heat transfer related behavior.

Conclusions

Although the observations described were made under certain well-defined operating conditions and by analyzing experimental data involving helium, argon, and nitrogen (as well as two separate sets of binary gaseous mixtures consisting of helium/argon and helium/nitrogen), these heat transfer related results are believed to apply generally (and qualitatively) to all possible combinations of light/heavy gas mixtures. However, what will tend to change most significantly in other cases are the flow ranges, as well as actual magnitude of performance enhancements, in which the improved heat transfer performance will occur with other mixtures of light and heavy gases. It is also possible that theoretical models of this behavior can be worked out (using the data presented herein) to allow reasonably valid predictions regarding the heat transfer related behavior of other gases and gas mixtures as a function of gas flow rates (or gas flow velocities) and other critical initial temperature conditions far removed from 100°C. To limit the scope and length of this paper, a theoretical analysis of the observed heat transfer behavior has not been presented. In any case, the experimental observations described are potentially very useful because they prove that, under certain conditions, gas streams consisting of binary mixtures containing helium diluted with a heavier gas are better heat transfer agents than pure helium alone. Even pure argon or pure nitrogen, under certain flow rate and temperature conditions, are capable of outperforming pure helium as a heat transfer agent. The cost savings that may be a result of applying this knowledge, in special situations in which the "right conditions" are extant, could be substantial.

Acknowledgments

The work of M. G. Pizzo in equipment fabrication and assembly, as well as in the data collection effort, is gratefully acknowledged. The author also acknowledges useful comments recommended by one of the reviewers of this paper, which were added in the "Laminar/Turbulent Flow Behavior/Heat Convection Mode" section.

References

[1] Vanco, M. R., "Analytical Comparison of Relative Heat-Transfer Coefficients and Pressure Drops of Inert Gases and Their Binary Mixtures," NASA TN D-2677, Feb. 1965.

[2] Giacobbe, F. W., "Heat Transfer Capability of Selected Binary Gaseous Mixtures Relative to Helium and Hydrogen," *Applied Thermal Engineering*, Vol. 18, No. 3–4, 1998, pp. 199–206.

[3] Holoboff, R., L'Hote, B., Speri, R., and Delcourt, O., "Gas Quenching with Helium," *Advanced Materials and Processes*, Vol. 143, No. 2, 1993, pp. 23–26.

[4] Publ. 22553C (Catalog 10A-1000-83), Fischer–Porter Co., Warminster, PA, 1983, pp. 1–40.

[5] Miller, R. W., *Flow Measurement Engineering Handbook*, McGraw–Hill, New York, 1983, pp. 14:45–14:59.

[6] Zemansky, M., *Heat and Thermodynamics*, 4th ed., McGraw–Hill, New York, 1957, pp. 89, 90.

[7] Wolf, H., *Heat Transfer*, Harper and Row, New York, 1983, pp. 174–176.

[8] Gray, D. E. (ed.), *American Institute of Physics Handbook*, 3rd ed., McGraw–Hill, New York, 1982, pp. 2:242, 2:243.

[9] Brokaw, R. S., "Approximate Formulas for Viscosity and Thermal Conductivity of Gas Mixtures," NASA TN D-2502, Nov. 1964, pp. 1–17.

[10] Iwasaki, H., and Kestin, J., "The Viscosity of Argon-Helium Mixtures," *Physica*, Vol. 29, 1963, pp. 1345–1372.

[11] Giacobbe, F. W., "Estimation of Prandtl Numbers in Binary Mixtures of Helium and Other Noble Gases," *Journal of the Acoustic Society of America*, Vol. 96, No. 6, 1994, pp. 3568–3580.

[12] Avallone, E. A., and Baumeister, T. (eds.), Marks' Standard Handbook For Mechanical Engineers, 10th ed., McGraw–Hill Inc., New York, 1996, pp. 3:47–48.