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A method for measuring the thermal heat transfer from a cylinder in axial turbulent flows for the best seven He–based binary gas mixtures

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Abstract. With the goal of intensifying turbulent free convection from heated vertical plates to cold gases, seven binary gas mixtures are examined in this technical note. Helium (He) is chosen as the principal gas while xenon (Xe), nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), (CH_4), tetrafluoromethane (CF_4) and sulfur hexafluoride (SF_6) are the companion gases. From thermal physics, the thermophysical properties affecting turbulent free convection of binary gas mixtures are the viscosity μ_{mix}, the thermal conductivity λ_{mix}, the density ρ_{mix}, and the heat capacity at constant pressure $C_{p,\mathrm{mix}}$. Invoking the similarity variable transformation, the system of two nonlinear differential equations is solved numerically by the shooting method and a fourth-order Runge-Kutta-Fehlberg algorithm. From the numerical temperature fields, the allied mean convection coefficients $\bar{h}_{\mathrm{mix}}/B$ changing with the molar gas composition w in the w domain [0, 1] are plotted in congruous diagrams for the seven binary gas mixtures under study.

1 INTRODUCTION

In general, the intensification of free convection is a difficult task because of the low fluid velocities that are normally imparted by gravitational flows. Owing to this adverse effect, it is of fundamental and practical interest to explore passive methods that are conducive to invigorating the free convection cooling of engineering devices. As quoted by Raithby and Hollands], with the exception of the work by Misuni and Kitamura and the few references cited therein, potential avenues for augmenting freebased binary gas mixtures that may be used in various facets of turbulent free convection. It is expected that the outcome of this paper will be useful to design engineers.

2.Turbulent free convection with binary gas mixtures

Fundamentally, the free convection mode comprises the molecular heat conduction mode accompanied by fluid motion. One feasible idea for invigorating the free convection mode may revolve around the beneficial attributes that certain binary gas mixtures may offer. Fundamentally, this is a physico-chemistry approach that rests on the interplay of the four intervening thermo-physical properties: viscosity η, thermal conductivity λ, density ρ, and isobaric heat capacity C_p and should fall under the category of passive techniques.

To begin the analysis, we designated h_{mix} as the convective coefficient of a binary gas mixture. Thereby, h_{mix} is isolated in Eq. (1) to allow it to vary with the thermo-physical properties η_{mix}, λ_{mix}, ρ_{mix} and $C_{p,mix}$ (herein the subscript mix entails to mixture of binary gases). This simple operation produces the adjoin proportionality

$$h_{mix} \alpha \lambda_{mix}{}^{2/3} \left(\frac{\rho_{mix} C_{P,mix}}{\mu_{mix}} \right)^{1/3} \tag{1}$$

In theory, each thermo-physical property η_{mix}, λ_{mix}, ρ_{mix}, $C_{p,mix}$ present Eq. (1) is a triple-valued function of the temperature T, pressure P, and molar gas composition w. In practice, once P and T are fixed, a single-value function h_{mix} (w) surfaces up.

3. Thermal conductivity

For the thermal conductivity of a binary gas mixture λ_{mix}, Schreiber at al. developed the matrix formula:

$$\lambda_{mix} = - \frac{\begin{vmatrix} L_{AA} & L_{AB} & x_A \\ L_{AB} & L_{BB} & x_B \\ x_A & x_B & 0 \end{vmatrix}}{\begin{vmatrix} L_{AA} & L_{AB} \\ L_{AB} & L_{BB} \end{vmatrix}} \tag{2}$$

Here, the elements of the upper and lower matrices are taken from the expressions:

$$L_{AA} = \frac{x_A^2}{\lambda_A} + \frac{25 x_A x_B}{8 A^*_{AB} \lambda_{AB}} \left(\frac{R}{C^0_{pA}} \right)^2 \left[\frac{25}{4} y_B^4 + \frac{15}{2} y_A^4 - 3 y_B^4 B^*_{AB} + 4 y_A^2 y_B^2 A^*_{AB} + \left(\frac{C^0_{pA}}{R} - 2.5 \right) \right] \tag{3}$$

$$L_{BB} = \frac{x_B^2}{\lambda_B} + \frac{x_A x_B}{2 A^*_{AB} \lambda_{AB}} \left(\frac{25}{4} y_A^4 + \frac{15}{2} y_B^4 - 3 y_A^4 B^*_{AB} + 4 y_A^2 y_B^2 A^*_{AB} \right) \tag{4}$$

$$L_{AB} = - \frac{5 x_A x_B y_A^2 y_B^2}{4 A^*_{AB} \lambda_{AB}} \left(\frac{R}{C^0_{pA}} \right) \left(\frac{55}{4} - 3 B^*_{AB} - 4 A^*_{AB} \right) \tag{5}$$

Where λ_A is the thermal conductivity of the gas component A, λ_B is the thermal conductivity of the gas component B and λ_{AB} is the interaction thermal conductivity.

Moreover, C^o_p is the isobaric heat capacity taken from the ideal gas model (see a forthcoming subsection), R is the gas constant, A^* and B^* are collision integral ratios, and x_q is the mole fraction of the species q. Also, y_p represents the mass ratio of species q, which is obtained from:

$$y_q^2 = \frac{M_q}{M_A + M_B} \tag{6}$$

Where M_q is the molar mass of species q . Besides, the interaction thermal conductivity λ_{AB} is evaluated with the equation

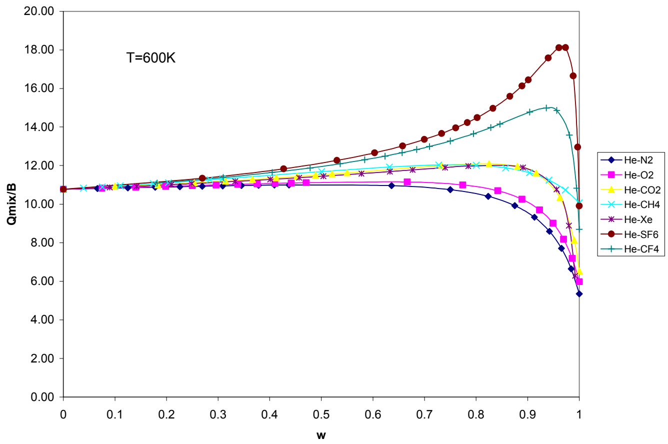
$$\lambda_{AB} = \frac{15}{8} R \left(\frac{M_A + M_B}{M_A M_B} \right) \eta_{AB} \tag{7}$$

4. CONCLUSIONS

Unquestionably, air constitutes the logical baseline case for comparison purposes in this study. From a practical perspective, it is instructive to contrast the performance of turbulent free convection delivered by the five binary gas mixtures He-CO_2, He-CH_4, He-N_2, He-O_2, and He-Xe against the turbulent free convection performance using air, both situation operating at the same temperature and pressure. To accomplish this, two figures showing the allied convective coefficient h_{mix} /B on the ordinate versus the molar gas composition w on the abscissa were prepared. For convenience, the constant B was introduced to absorb those quantities that are unrelated to the thermo-physical properties., so that h_{mix} /B is conceived as an allied convective coefficient of the binary gas mixture. The format of the abscissa indicated that the left extreme w=0 belongs to the primary gas component He, whereas the right extreme w=1 corresponds to the secondary gas components CO_2, CH_4, N_2, O_2 and Xe. Included also in the figures is a horizontal line related to the allied convective coefficient for air h_a /B, the so-called baseline case.

Gas	M (g/mol)	ρ (kg/m^3)	η (μPa.s)	λ (mW/m K)	C_p^0 (J/kg.K)
He	4.00	0.1624	19.92	155.70	5199.11
CH_4	16.04	0.6553	11.19	34.89	2230.47
N_2	28.01	1.1379	17.96	25.88	1039.66
O_2	32.00	1.3004	20.78	26.64	918.21
CO_2	44.01	1.7964	15.08	16.79	848.40
CF_4	88.00	3.5410	17.34	15.16	699.36
Xe	131.3	5.3610	23.20	5.52	158.49
SF_6	146.1	5.8585	29.70	13.20	671.39

Table 1 : Thermophysical properties of the pure gases at 300 K and 1 atm



Figur1: Influence of the molar gas composition w upon the relative heat transfer rate Q_{mix} / B for the binary gas mixtures at 600 K and 1 atm.

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