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Two target parameters, the heat transfer Q_{mix} /B and the drag force Fd_{mix} /C are susceptible to the molar gas composition w of the six gas–gas mixtures in the w-domain [0, 1]

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ABSTRACT

This paper addresses the laminar boundary layer flow of selected binary gas mixtures along a heated flat plate. To form the binary gas mixtures, light helium (He) is the primary gas and the heavier secondary gases are nitrogen (N_2), oxygen (O_2), xenon (Xe), carbon dioxide (CO_2), methane (CH_4), tetrafluoromethane (CF_4) and sulfur hexafluoride (SF_6). The central objective in the work is to investigate the potential of this group of binary gas mixtures for heat transfer intensification. From fluid physics, two thermophysical properties: viscosity η and density ρ influence the fluid flow, whereas four thermophysical properties: viscosity η, thermal conductivity λ, density ρ, and heat capacity at constant pressure C_p affect the forced convective heat transfer. The heat transfer augmentation from the flat plate is pursued by stimulating the forced convection mode as a whole. In this regard, it became necessary to construct a specific correlation equation to handle binary gas mixtures owing Prandtl number $\Pr \in (0.1, 1)$. The rate of heat transfer Q between a heated plate and a cold fluid is calculated with:

$$Q_{mix} / B = \left(\frac{\lambda_{mix}^{0.623} \rho_{mix}^{0.500} C_{p,\,mix}^{0.377}}{\eta_{mix}^{0.123}} \right) \qquad (1)$$

If the surface area of the plate A and the temperature difference $T_w - T_\infty$ are specified, the only possible way for intensifying the rate of heat transfer Q is by enlarging the magnitude of the average heat transfer coefficient $\bar{h}$. This is precisely the main goal to be pursued in the present paper.

The average heat transfer coefficient $\bar{h}$ in laminar boundary layer flows of incompressible, viscous fluids along heated flat plates depends on the dimensionless fluid temperature gradient at the plate $\theta'(0)$. It is given by the Prandtl number function f (Pr).

Keywords: Free convection, heat transfer, binary gas mixtures, thermophysical properties , Prandtl number, film temperature

I. *Introduction*

Free convection flows confined to square cavities occur in several branches of engineering, geophysics, environmental sciences, etc. By solving the steady Navier-Stokes and energy equations, analysts are able to predict laminar convective flows at any Rayleigh number, in principle. Yet as the impressed wall temperature difference rises and / or the size of the square cavity grow, all laminar convective flows become turbulent at sufficiently high Rayleigh numbers.

Many of the laminar convective flows turn ocillatory over a certain range of Rayleigh numbers. The oscillatory regimes usually lie some where between the laminar and turbulent regimes.

A number of numerical and experimental works have been carried out in the past decades in an attempt to predict turbulent convective flows in closed square cavities in a qualitative manner. The efficacious design of gas-filled square cavities rests on three key elements: 1) the sizing of the cavity, 2) the specification of the temperature difference $T_H - T_c$ at the vertical walls, and 3) the selection of the working fluid. The present study deviates significantly from earlier studies. Instead, the study is centered on special gaseous medium that is expected to intensification. Attention is focused primarily on the usage of binary gas mixtures formed with helium (He) and xenon (Xe), although the possibility of mixing other single gases with He is also examined.

II. *Kinetic theory of gases*

The kinetic theory expressions for the viscosity (η) read as:

$$\eta = \frac{5}{16} \frac{(\pi m k T)^{1/2}}{\pi \sigma^2 \Omega^{*(2,2)}} f_\eta, \qquad (2)$$

The collision diameter σ is defined as the separation distance when the intermolecular potential function is equal to zero. ρ is the number density.

It should be mentioned that because the viscosity and diffusion coefficients are concerned with transporting momentum and mass, respectively, and therefore do not

involve in internal degree of freedom, the Chapman-Enskog theory retains its useful form, but the collision integrals, must be averaged over all possible relative orientations occurring in collisions.

The kinetic theory expression for the viscosity of mixtures reads as:

$$\eta_{mix} = -\frac{\begin{vmatrix} H_{11} & H_{12} & \cdots & H_{1v} & x_1 \\ H_{21} & H_{22} & \cdots & H_{2v} & x_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ H_{v1} & H_{v2} & \cdots & H_{vv} & x_v \\ x_1 & x_2 & \cdots & x_v & 0 \end{vmatrix}}{\begin{vmatrix} H_{11} & H_{12} & \cdots & H_{1v} \\ H_{21} & H_{22} & \cdots & H_{2v} \\ \vdots & \vdots & \ddots & \vdots \\ H_{v1} & H_{v2} & \cdots & H_{vv} \end{vmatrix}} \tag{3}$$

Where

$$y_q^2 = \frac{M_q}{M_A + M_B} \tag{4}$$

Where M_q is the molar mass of species q. The interaction thermal conductivity λ_{AB} is calculated by the following relation:

$$\lambda_{AB} = \frac{15}{8} R \left(\frac{M_A + M_B}{M_A M_B} \right) \eta_{AB} \tag{5}$$

$$B = 0.1 \left(\frac{T_H - T_c}{T_{ref}} \right)^{1/3} \tag{6}$$

A_{ij}^* is the ratio of collision integrals, *x* is the mole fraction of components. Subscript i represents the heavier component and subscript j represents the lighter component of the i-j pair.

In the basic development of the theory of Chapman-Enskog only binary elastic collisions between the molecules are considered and also molecules are considered to be without internal degrees of freedom. Since the internal degrees of freedom of poly-atomic molecules involve in transporting energy in gases, thus this theory can not be employed to predict thermal conductivity.

The theoretical expressions for the thermal conductivity of dilute, multi-component polyatomic gas mixtures were first derived from a solution of the kinetic theory equation found by Wang-Change-Uhlenbeck, employing expansion vectors that depend separately upon the translational and the internal contributions to the heat flux.

A simplified version of the thermal conductivity of an atom-diatom mixture in the limit of zero density was developed by Schreiber et al.:

$$\lambda_{mix} = -\frac{\begin{vmatrix} L_{AA} & L_{AB} & x_A \\ L_{AB} & L_{BB} & x_B \\ x_A & x_B & 0 \end{vmatrix}}{\begin{vmatrix} L_{AA} & L_{AB} \\ L_{AB} & L_{BB} \end{vmatrix}} \tag{7}$$

Table 1 -- Thermophysical properties of the pure gases at 300 K and 1 atm (4)

Gas	M (g/mol)	ρ (kg/m^3)	η (μPa.s)	λ (mW/mK)	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

(6)

Table 2 -- Thermophysical properties of the pure gases at 600 K and 1 atm

Gas	M (g/mol)	P (kg/m^3)	η (μPa.s)	λ (mW/mK)	C_p^0 (J/kg.K)
He	4.00	0.0802	32.22	252.40	5192.87
CH_4	16.0	0.3215	19.43	88.92	3273.02
N_2	28.0	0.5613	29.60	43.92	1075.14
O_2	32.0	0.6413	34.67	50.74	1003.25
CO_2	44.0	0.8825	28.00	41.55	1076.23
CF_4	88.0	1.7632	30.06	40.32	989.21
Xe	131.3	2.6331	42.92	10.26	158.58
SF_6	146.1	2.9284	23.65	32.70	933.23

III. *LIST OF FIGURES*

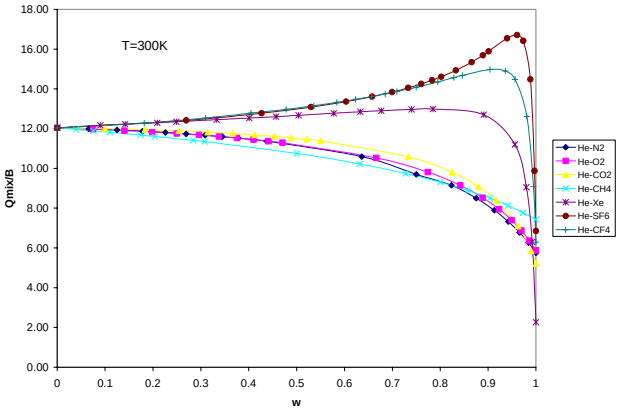

Fig. 1 Influence of the molar gas composition w upon the relative heat transfer rate Q_{mix}/B for the binary gas mixtures at 300 K and 1 atm.

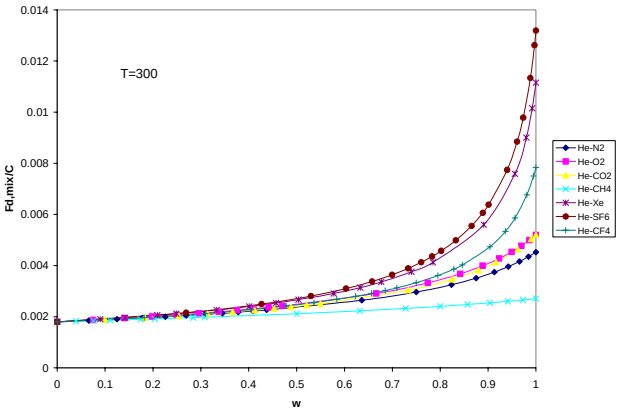

Fig. 2 Influence of the molar gas composition w upon the relative drag force Fd_{mix}/C for the binary gas mixture at 300 K and 1 atm.

IV. CONCLUSION

First and foremost, a special correlation equation for binary gas mixtures owing $Pr \in (0.1, 1)$ had to be constructed from the original tabulated data for the broad Prandtl number spectrum spanning from 0.001 to 1000. Based on the seven He–based binary gas mixtures analyzed at the film temperatures 300 K sharing a pressure of 1 atm, the principal conclusion that may be drawn is that the He+SF_6 mixture is unequivocally the best binary gas mixture for laminar boundary layer flow characterized by Re $< 5 \times 10^5$.

This is so regardless of the film temperature considered. Based on the light primary He, the heat transfer enhancement jumps up to 39% for 300 K and up to 68% for 600 K; both quantities being of great significance. As the secondary conclusion, the He+CF_4 mixture is the second best binary gas mixture at the two film temperatures too. In this case, the heat transfer enhancement

When referred to He amounts to 24% at 300 K, while at 600 K it is slightly higher reaching 39%. For the same pair of binary gas mixtures, either He+SF_6 or He+CF_4, it is evident that the heat transfer enhancements show improvement with elevations in film temperature.

NOMENCLATURE

A_S surface area of plate (m^2)
B overall parameter related to Q
B_2 second virial coefficient (m^3 $mole^{-1}$)
C overall parameter related to Fd
C_p mass heat capacity at constant pressure (J kg^{-1} K^{-1})
C_p^0 molar heat capacity of an ideal gas at constant pressure (J $mole^{-1}$ K^{-1})
C_v^0 molar heat capacity of an ideal gas at constant volume (J $mole^{-1}$ K^{-1})
$\overline{C_f}$ average skin friction factor, $\overline{\tau_w}/(\rho u_\infty^2/2)$
Fd drag force (N)
$\overline{h}$ average heat transfer coefficient (Wm^{-2} K^{-1})
$\overline{Nu}_L$ average Nusselt number, $\overline{h}\,L/\lambda$

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