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ENHANCEMENT OF HEAT TRANSFER BY THE USE OF MIXTURES

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ABSTRACT

The effect of gaseous mixture composition on heat transfer coefficient calculated by means of Dittus–Boelter, Petukhov–Popov and Sleicher–Rouse equations has been studied for H_2–CO_2: H_2–Ar: He–Kr and N_2–CO systems. It has been shown that for the first three systems for certain conditions of flow there exists a mixture which has higher heat transfer coefficient value than either of its pure components.

INTRODUCTION

The present paper will examine comparatively the effect of mixture composition on the heat transfer coefficient h as predicted by the equations of Dittus–Boelter [1], Petukhov–Popov [2] and Sleicher–Rouse [3] *. Local heat transfer coefficient behavior of hydrogen–carbon dioxide, hydrogen–argon, helium–krypton (molecular weight ratios 1:22, 1:20, and 1:21, respectively) and nitrogen–carbon monoxide (molecular weight ratio 1:1) has been studied. Only the hydrogen–carbon dioxide system will be discussed in detail in this paper.

The Dittus–Boelter equation

The Dittus–Boelter equation

$$(\mathrm{Nu}) = 0.023\,(\mathrm{Pr})^n(\mathrm{Re})^m \tag{1}$$

has been in use for many years. It is applicable to fully developed fluid flow (that is no hydrodynamic or thermal entry effects exist) and for heat transfer rates sufficiently low that constant fluid properties obtain. The regime of its applicability has been given as $0.7 < \mathrm{Pr} < 350$ and $4 \times 10^3 < \mathrm{Re} < 10^6$. The value of m commonly accepted is 0.8. Various values of n have been proposed, among them 0.3 for a fluid being cooled and 0.4 for one being heated. This work uses 0.3, although the exact value is only marginally germain to the generality of the results to be reported.

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* Compare with the discussion by Serksnis et al. [4].

The Petukhov–Popov equation

The Petukhov–Popov equation

$$\mathrm{Nu} = \frac{(\xi/8)\mathrm{Re}\,\mathrm{Pr}}{K_1(\xi) + K_2(\mathrm{Pr})(\xi/8)^{1/2}(\mathrm{Pr}^{2/3}) - 1} \tag{2}$$

where

$\xi = (1.82 \log \mathrm{Re} - 1.64)^{-2}$

$K_1(\xi) = 1 + 3.4\xi$

$K_2(\mathrm{Pr}) = 11.7 + 1.8\ \mathrm{Pr}^{-1/3}$

like that of Dittus–Boelter, refers to fully developed fluid flow and constant fluid properties. The authors give as the regime of applicability $0.5 < \mathrm{Pr} < 2000$ and $10^4 < \mathrm{Re} < 5 \times 10^6$. The equation is stated to correlate local heat transfer coefficients within 1%.

The Sleicher–Rouse equations

Two equations are offered by these authors [3]. Both, again refer to fully developed flow and constant fluid properties. One equation (herein referred to as "general")

$$\mathrm{Nu} = 5 + 0.015\ \mathrm{Re}^a \mathrm{Pr}^b \tag{3}$$

where

$a = 0.88 - 0.24\ (4 + \mathrm{Pr})$

$b = 1/3 + 0.5\ \mathrm{e}^{-0.6\mathrm{Pr}}$

correlates heat transfer coefficients in liquid and gas systems to within 10% when used in the ranges $0.1 < \mathrm{Pr} < 10^6$ and $10^4 < \mathrm{Re} < 10^6$. A more restricted equation applicable to gases only (referred to as "gas")

$$\mathrm{Nu} = 5 + 0.012\ \mathrm{Re}^{0.83}\ (\mathrm{Pr} + 0.29) \tag{4}$$

correlates within the range of $0.6 < \mathrm{Pr} < 0.9$ to 4% with eqn. (3).

METHOD

Physical system

It is assumed that heat is transferred from flowing gas to a smooth tube having an inside diameter of 2.3 cm and a configuration of apparatus such that fully developed turbulent flow obtains.

TABLE 1

Properties of hydrogen–carbon dioxide mixtures

Mole fraction hydrogen	Viscosity[a] $\mu \times 10^7$ (Pa s)	Thermal[a] conductivity $k \times 10^4$ (W m^{-1} K^{-1}	Density[b] (kg^{ρ} m^{-3})	Heat[c] capacity C_p (J kg^{-1} K^{-1})	Prandtl number Pr
0.000	136.9	151	1.96	837	0.76
0.100	138.0	214	1.78	905	0.59
0.142	139.0	239	1.70	966	0.56
0.250	140.6	322	1.50	104×10^1	0.45
0.355	141.5	419	1.30	117×10^1	0.39
0.500	141.7	565	1.03	142×10^1	0.36
0.750	134.1	950	0.558	245×10^1	0.35
0.901	116.3	1319	0.275	477×10^1	0.42
1.000	85.4	1691	0.893×10^{-1}	142×10^2	0.72

[a] All values taken from ref. 6 but converted to S.I. retaining the same number of significant digits.

[b] All values calculated from ideal gas law, $PV = RT$.

[c] Heat capacity values for pure hydrogen and carbon dioxide calculated from experimentally determined equations [5]. The mixture heat capacity values were, however, obtained as means of pure components weighted by mass fractions.

Properties of fluids

Because of the limited range of experimental data available [5–9], all operations of the heat transfer system were assumed to be carried out at a pressure of 1 standard atmosphere (1.013×10^5 Pa) and 0°C. Further, conditions were chosen such that for results to be acceptable the pressure drop arising from flow was not greater than 5% of the mean pressure. Accordingly, it was possible to treat the pure components and mixtures of fluids as ideal gases with respect to density and heat capacity. Experimental heat capacity values for the pure components were used. Mixture densities and mixture heat capacities were calculated from the pure component values using ideal gas linear mixing rules. However, experimental values of viscosity and thermal conductivity were used for both, the pure gases and their mixtures. Table 1 lists data used for the hydrogen–carbon dioxide system.

Calculation

Initially a bulk gas velocity for hydrogen was chosen. For the conditions described 41.598 m s^{-1} was convenient because the resulting Reynolds number ($\mathrm{Re}_{\mathrm{H}_2}$) was 10000, the lowest value applicable to all the equations used. Then pure carbon dioxide and several mixtures of hydrogen and carbon dioxide were used and h calculated for them at the same bulk gas velocity. This condition of uniform bulk gas velocity will hereinafter be referred to as constraint (A). Other constraints will later be considered.

RESULTS

Constraint of constant bulk velocity

Numerical results obtained by using eqns. (1)–(4) for pure hydrogen, pure carbon dioxide, and mixtures thereof are shown in Fig. 1. Condition (A) applies to all curves and the basic hydrogen flow rate (41.598 m s^{-1} giving $Re_{H_2} = 10000$) also is the same for all.

Excluding for the moment the curve from the Dittus–Boelter equation, which has been criticized by both Petukhov and Sleicher, we see that the values for h for the pure components agree closely. Indeed one suspects that they must do so, because the equations have been written in a form and using coefficients chosen for the purpose of getting close agreement with experimental values determined for pure substances. However, when mixtures are considered, we find that the disagreement between the values given by eqns. (2)–(4) may increase by almost an order of magnitude. Indeed, this disagreement is now greater than is the difference between the pure component values given by Dittus–Boelter and those given by the newer equations.

Not only does a numerical variation appear, but the form of the response of the equation to change in composition also differs between equations. The equation of Petukhov and Sleicher's gas equation show a maximum; Sleicher's general equation does not, but shows an inflection. Further inspection of Fig. 1 shows that within the given Pr number ranges [see eqns. (1)–(4)] eqn. (3) (Sleicher-general) is functionally

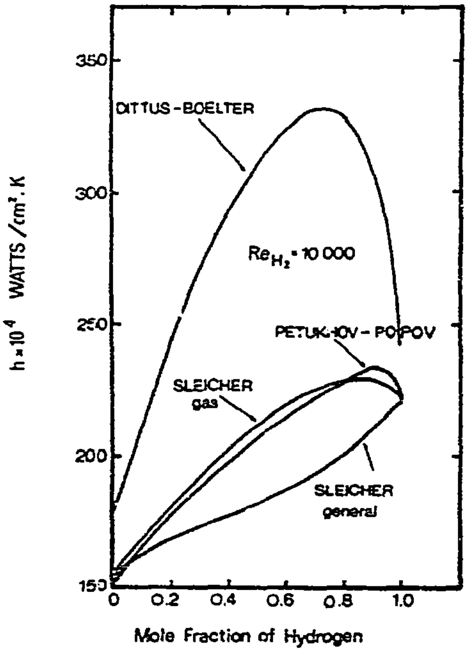


Fig. 1. Heat transfer coefficient as a function of mixture composition using eqns. (1)–(4). See footnote on p. 32.

incompatible with eqns. (1), (2) and (4) (Dittus–Boelter, Petukhov and Sleicher-gas). These equations differ in values of $\Delta h/\Delta x$ (h = heat transfer coefficient; x = mole fraction of H_2). Indeed, the values differ not merely in magnitude at $x \approx 0$ and $x \simeq 1.0$, but much more significantly, differ in sign at $x \simeq 1.0$. We conclude that all four equations cannot be functionally correct at the same time for the given binary mixture.

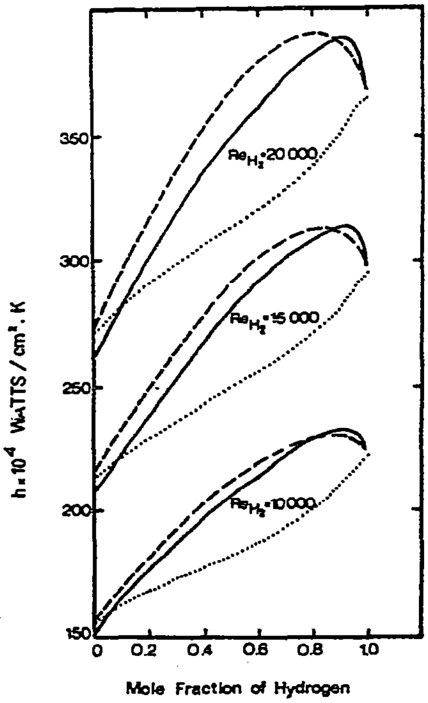
These discrepancies do not disappear as Re_{H_2} is increased. Figure 2 reproduces the Petukhov and Sleicher curves for $\mathrm{Re}_{H_2} = 10000$ already shown in Fig. 1 and adds corresponding curves for $\mathrm{Re}_{H_2} = 15000$ and $\mathrm{Re}_{H_2} = 20000$. Changes in detail can be seen but the general forms remain, and already noted discrepancies seem to increase somewhat.

Other constraints

Thus far, reporting has been confined to the case of constant bulk gas velocity. Other restraints which are equally realistic are easily imagined. For example

(B) constant pressure drop;

(C) constant power input for flow generation;



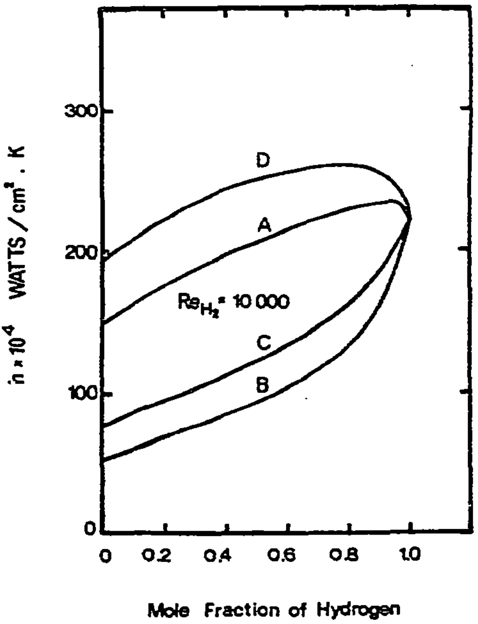


Fig. 2. Heat transfer coefficient for one basic lighter component flow, but for different flows of the lighter component. Petukhov–Popov (————); Sleicher-gas (- - - - -); Sleicher-general (· · · · · ·). See footnote on p. 32.

Fig. 3. Heat transfer coefficient for one basic lighter component flow, but for different flow constraints. See footnote on p. 32.

(D) the fourth condition arises knowing that, in many engineering situations, the pressure drop causing flow is generated by a centrifugal compressor. If this compressor is left unaltered with respect to geometry and speed, the available pressure drop will depend on gas density, and, in the present case, the composition of the hydrogen–carbon dioxide mixture. The criterion adopted in this paper was that the pressure drop available was that required for hydrogen multiplied by the ratio of the density of the gas mixture to that of hydrogen.

Results using these constraints, with constraint (A) included for comparison, are shown in Fig. 3 for the case of $Re_{H_2} = 10000$ using the equation of Petukhov and Popov. Lines are marked A, B, C and D to conform with the constraints. The use of Sleicher's gas equation results in a very similar diagram. Sleicher's general equation yields lines always lower (except for the pure components) and with some distortion of shape. Dittus–Boelter, as might have been expected from inspection of Fig. 1, gives uniformly higher values, a curve D which is much more strongly convex upwards, curve C is almost straight and curve B only slightly concave upwards.

Generally, curves B and C are not very interesting but D represents a situation which, if true, might well be important.

DISCUSSION

For processes in which gas has to be heated or cooled, but in which the composition of the gas is governed by the required output of the process itself, the foregoing is relevant, only inasmuch as it influences the determination of the areas of heat transfer surfaces. However, processes do exist in which the gas is present primarily for heat transfer, and the gas composition is under the control of the designer. Gas cooling of nuclear reactors and hydrogen cooling of alternators are examples of the latter situation, and, because the performance of the equipment is dependent on the effectiveness of heat transfer, it would seem profitable to examine more closely the findings of this paper. Clearly, factors in addition to heat transfer would have to be considered. In the cases cited, neutron-capture, explosion hazards, reactivity of the gas with the equipment would be obvious matters for investigation.

Three of the four equations studied indicate a possible maximum in the value of h, at least for some flow conditions*. Equations (2) and (4) agree most closely and indicate a modest maximum. Equation (1) indicates the existence of a large maximum, but this equation is suspect because it predicts h for pure substances more poorly than do the other three equations. These findings were not merely confined to the hydrogen–carbon dioxide system but were duplicated in almost every feature by the systems hydrogen–argon and helium–krypton. The system nitrogen–carbon monoxide shows none of these effects. The possibility of enhancement of heat

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* When these results are considered (Figs. 1–3), please refer also to the empirical ranges of validity cited for each of the given heat transfer equations [eqns. (1)–(4)].

transfer by the use of mixtures would seem to be sufficiently important to be a considerable spur to the carrying out of at least some simple tests.

A word of warning. As the reader is well aware, these findings are the outcome of the use of equations which, while excellent for pure substances, are perhaps of limited validity for gaseous mixtures *. Indeed, as shown (Fig. 1–3) not all of the equations are functionally similar. Thence, even the newer eqns. (2), (3) and (4) do not appear all to be "correct", except to a lower level of accuracy than is believed by their creators (see, for instance, Fig. 1).

The need for work aimed at establishing *h* for several mixtures is clearly indicated. Such work might confirm the existence of a worthwhile effect which could be exploited. It might indicate that one, or none, of the equations was reliable—a not negligible gain. Whatever the outcome, the dangers of assuming that what is true for pure substances must be true for mixtures will have been substantiated.

NOMENCLATURE

C_p	Specific heat at constant pressure
h	Heat transfer coefficient
k	Thermal conductivity
m	Constant
n	Constant
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Re_{H_2}	Reynolds number for bulk hydrogen flow
x	Mole fraction
μ	Dynamic viscosity
ρ	Density

ACKNOWLEDGEMENT

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