A Mixture of Pure Gases that Produce Maximum Heat Transfer Characteristics for Quenching

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Gas quenching provides a desirable alternative to conventional liquid quenching in heat treating from the standpoint of quality, safety, and environmental issues. There is convincing evidence that gas-quenched parts heat treated in vacuum furnaces are clean and bright and do not require a postcleaning process that may result in additional production costs. The cooling rates for thicker section parts that are heat treated may be increased by increasing the magnitude of the heat transfer coefficient of the gaseous medium. This heat transfer coefficient, which is dependent on the thermal conductivity, viscosity, specific heat, and density of gases can be maximized by utilizing gas mixtures instead of pure gases. Substantial increases in heat transfer rates for the gas quenching process can be achieved by appropriately mixing gases such as helium and argon.

Keywords	pressure quenching, quenching, vacuum heat treating

1. Introduction

In general, heat treatment of low-alloy and high-alloy steel parts is a manufacturing operation involving heating to an elevated temperature followed by controlled cooling to obtain specific microstructures and a suitable combination of mechanical properties. The utility of these steels for various applications involves the ability of the mechanical properties to be altered by controlling the way the parts are heated and then cooled. In essence, the resulting change in these properties occurs principally due to the different microstructural constituents, which are achieved by varying types of cooling rates.

The primary function of a quenching medium is to control the heat transfer rates from manufactured parts during the cooling process and to produce the desired hardness, strength, and toughness. The quenchant must be able to minimize undesirable distortion as well as control residual stresses by providing uniformity over the total surface of the manufactured part.

The fastest growing technology in heat treatment of metals is gas quenching in a vacuum furnace (Ref 1), a process that is capable of producing clean and bright metals. If either ferrous or nonferrous metallic parts are heated under high vacuum conditions (10^{-4} to 10^{-2} mbars), volatile oxide impurities are readily removed. Consequently vacuum heat treatment can be considered a cleaning process.

Despite the fact that quenching can be performed in a vacuum furnace with various media including oil and aqueous polymers, gas quenching is the most common method (Ref 2, 3). Gas quenching is typically performed by pressurizing the furnace after the austenitizing heat treatment phase has been completed. Most gas quenching is done with argon, helium, hydrogen, or nitrogen (Ref 1). In single chamber vacuum furnaces, the load is heated and gas quenched in the same chamber. Two quench-process designs are common: external gas fan and heat exchanger and internal high-capacity fan and heat exchanger.

Gas mixing allows the engineer to adjust a particular quenching operation to higher heat transfer coefficients than

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Nomenclature	
A	surface area of the body
A_{12}, A_{21}	interaction parameters of the gas mixture
C	constant
c_p	specific heat of a pure gas
d	characteristic length, diameter
F	correction function
h	average heat transfer coefficient
h_m	average heat transfer coefficient of the gas mixture
K	constant
M	molecular weight
Nu	average Nusselt number
Pr	Prandtl number, $Pr = \mu c_p/\kappa$
Q	heat removal rate
Re	Reynolds number, $Re = (\rho u_m d)/\mu$
T_s	surface temperature
T_∞	free stream gas temperature
u_∞	free stream gas velocity
x	mass fraction of gas 2
Greek symbols	
α, β	constants
ρ	density of a pure gas
κ	thermal conductivity of a pure gas
μ	viscosity of a pure gas
Φ_{12}, Φ_{21}	viscosity parameters of the gas mixture
Subscripts	
1, 2	pure gas
m	mixture of gases

might be achievable with a pure gas. Lhote and Delcourt (Ref 2, 3) have reported the relative heat transfer characteristics of a gas mixture consisting of 70% He + 30% Ar.

Three major factors contribute to heat transfer processes in vacuum furnaces: the temperature difference between the part and the circulating gas, the surface area of the part exposed to the gas, and more importantly the heat transfer coefficient. For a given application and heat treatment, the first two factors are essentially unaltered, whereas the third factor can be modified. It is therefore of theoretical interest to determine whether the combination of two different pure gases yields levels of maximum heat transfer augmentation unattainable when either pure gas acts independently.

The enhancement of heat transfer associated with external flows can be accomplished through two broad techniques: active and passive. Of the two, the passive technique, through surface roughness and displacement promoters, is more commonly employed in industrial applications (Ref 4). The most salient feature of passive techniques is that they do not need external power. However, these techniques cannot be applied to the gas quenching process of manufactured parts simply because the surfaces of workpieces cannot be modified.

The set of calculations necessary for the prediction of maximum heat transfer coefficients utilizing gas mixing for rapid gas cooling operations is reported.

2. Analysis of Forced Convective Cooling using a Mixture of Pure Gases

From a strict physical standpoint, convection heat transfer consists of two mechanisms operating simultaneously. The first is the energy transfer by heat conduction, and superimposed upon it is the energy transfer by fluid motion. In the latter, the fluid moves by virtue of an external force, which in the case of external forced convection is caused by either a fan or a blower.

The rate of heat transmission by convection between the surface of a solid body and a fluid can be calculated from the venerable Newton's equation of cooling (Ref 5):

$$Q = hA\Delta T \qquad \text{(Eq 1)}$$

where h designates the average heat transfer coefficient by forced convection. In view of the fact that these quantities are not necessarily constant over a surface, the convection heat transfer coefficient may vary from point to point. However, for most engineering applications the trend is to focus on average values.

The mathematical analysis of forced convection heat transfer is exceedingly intricate because it depends on (a) the body geometry, (b) several thermophysical properties of the fluid such as density, specific heat, thermal conductivity, and viscosity, and (c) the average velocity of the fluid flow.

For specific situations of forced convection heat transfer where the fluid medium is a gas, the motion of which remains fixed, the only possible option for augmenting the average heat transfer coefficient, h, is to alter the conduction mechanism. This route, in turn, results in a modification of the magnitude of the thermal conductivity.

From dimensional analysis (Ref 5), the heat transfer coefficient, h, is recast in terms of the Nusselt number and later conveniently expressed by a correlation equation of power form:

$$\text{Nu} = CRe^{\alpha}Pr^{\beta}F \qquad \text{(Eq 2)}$$

Here, the numerical values of the constants C, α and β, depend on the nature of the surface geometry and the type of flow (laminar or turbulent). There are, however, other factors that may make the heat exchange process very complex, and a correction function F is therefore added to the above Nusselt equation to obtain a greater generality and a better balance between predictions and experiments (F is commonly of the form $(Pr/Pr_s)^r$ or $(\mu/\mu_s)^r$, where the subscript s designates evaluation of the properties at the surface temperature and r depends on the case). The preceding equation has been used to investigate heat transfer by forced convection through, along, and across circular tubes and tested successfully against an enormous number of data points.

Solving explicitly for h in Eq 2 permits the functional relation:

$$h = C\frac{\kappa}{d}\left(\frac{\rho u_{\infty}d}{\mu}\right)^{\alpha}\left(\frac{\mu c_p}{\kappa}\right)^{\beta}F \qquad \text{(Eq 3)}$$

whose equivalent form reduces to

$$h = K\rho^{\alpha}c_p^{\beta}\kappa^{1-\beta}\mu^{\beta-\alpha} \qquad \text{(Eq 4)}$$

where $K = CFu_{\infty}^{\alpha}d^{1-\alpha}$.

Turning the attention to the density of a mixture of gases, this density may be expressed as:

$$\rho_m = (1 - x)\rho_1 + x\rho_2 \qquad \text{(Eq 5)}$$

and the specific heat

$$c_{pm} = (1 - x)c_{p1} + xc_{p2} \qquad \text{(Eq 6)}$$

In Eq 5 and 6, the subscripts 1 and 2 refer to each of the pure gases, and x denotes the composition, that is, the mass fraction of gas 2.

Contrary to what might be thought, the thermal conductivity of a mixture of gases is not a linear function of the composition. In general, if the constituent molecules differ greatly in polarity, the conductivity of the mixture is greater than what would be predicted from the average of molar fractions. For nonpolar molecules, one observes a contrary tendency, and this tendency becomes more pronounced as the difference in molecular weight of the constituent elements becomes greater (Ref 6).

Various reviews have been published that together provide a compendium of the diverse methods of calculating the thermal conductivities of mixtures (Ref 7-11). Moreover, many theoretical studies have explained the problems, deviations, and limitations of the diverse methods. The theoretical calculation

of the conductivity of mixtures of noble gases has been developed in considerable detail and has been reported reasonably well in other studies (Ref 18). The problems found when employing this theory arise when one attempts to simplify the complicated equations, when one elects a representative intermolecular power in order to evaluate these integrals of collision, and when one extends this formulation to mixtures of polyatomic gases. The first problem has been expressed by researchers who, for diverse methods, break the infinite system of equations that have emerged from the rigorous theory in order to offer a first approximation (monoatomic), a second approximation, and so on (Ref 12-18). In the majority of the cases, the first approximation is sufficient because the uncertainties in determining the correct function of intermolecular potential and in determining the polyatomic corrections generally make unnecessary an effort to calculate the monoatomic term with great precision. However, Brokaw (Ref 12, 13) developed a second approximation with great detail.

The most difficult problem encountered by these researchers is to correct the monoatomic value of the polyatomic molecules. Many techniques have been proposed, all of which involve approximations and are justified only through comparison of the calculated results of experimental values. Among the most useful formulas are those of Wassiljewa, Mason, and Saxena (Ref 19), and Brokaw (Ref 12, 13). Other proposed methods have been generally rejected either for following an erroneous criterion or for a combination of erroneous criteria and a desire to pick simple techniques. A compendium of methods have been published more recently (Ref 20).

On the basis of attempts to utilize the above-cited methods, the method that appears best for the estimation of the coefficient of thermal conductivity of a mixture of noble gases at low pressure is the one proposed by Wassiljewa, which has intrinsic errors of <2%. The appropriate predictive equation is:

$$\kappa_m = \frac{\kappa_1}{\left[1 + A_{12}\left(\frac{x}{1-x}\right)\left(\frac{M_1}{M_2}\right)\right]} + \frac{\kappa_2}{\left[1 + A_{21}\left(\frac{1-x}{x}\right)\left(\frac{M_2}{M_1}\right)\right]} \tag{Eq 7}$$

Here, M_1 is the molecular weight of gas 1, and the interaction parameters A_{12} and A_{21} (Ref 19) are given by the linear relations:

$$A_{12} = 1.065\Phi_{12} \quad A_{21} = 1.065\Phi_{21} \tag{Eq 8}$$

respectively, where Φ_{12} and Φ_{21} are the viscosity parameters of the gas mixture (Wilke, Ref 21),

$$\Phi_{12} = \frac{\left[1 + \left(\frac{\mu_1}{\mu_2}\right)^{1/2}\left(\frac{M_2}{M_1}\right)^{1/4}\right]^2}{\left(8\left[1 + \left(\frac{M_1}{M_2}\right)\right]\right)^{1/2}} \tag{Eq 9}$$

and

$$\Phi_{21} = \left(\frac{\mu_2}{\mu_1}\right)\left(\frac{M_1}{M_2}\right)\Phi_{12} \tag{Eq 10}$$

As for the viscosity, the binary gas mixtures generally do not depend linearly on composition; mixture viscosities are commonly greater than the predicted ones by a molar fraction average. Presence of a viscosity maximum (resulting this maximum greater than each of the pure components) has been deeply studied by several authors (Ref 22), and it seems that these maxima may be found in polar gas and nonpolar gas mixtures with quite different molecular weights, when pure components' viscosity are almost equal (this is the case of a helium/argon mixture, see Fig. 2).

According to the simplified method proposed by Wilke (Ref 21), mixture viscosity may be calculated:

$$\mu_m = \frac{\mu_1}{\left[1 + \Phi_{12}\left(\frac{x}{1-x}\right)\left(\frac{M_1}{M_2}\right)\right]} + \frac{\mu_2}{\left[1 + \Phi_{21}\left(\frac{1-x}{x}\right)\left(\frac{M_2}{M_1}\right)\right]} \tag{Eq 11}$$

offering errors <2%.

With the objective of maximizing the convective heat transfer coefficient, h, with respect to the composition of the gas mixture, x, Eq 4 has been particularized for a mixture. That is:

$$h_m = K_m\rho_m^\alpha c_{pm}^\beta \kappa_m^{1-\beta}\mu_m^{\beta-\alpha} \tag{Eq 12}$$

For the case of mixture of gases, it is reasonable to assume that K_m do not depend on x. Then, h_m is a function of four variables, ρ_m, c_{pm}, κ_m, and μ_m, that in turn are functions of x and the properties of the pure gases. Replacing in Eq 12 the Eq 5, 6, 7, and 11, the maximum heat transfer coefficient, $(h_m)_{max}$, is reached for a value of $x = x_c$ obtained from $dh_m/dx = 0$ (that satisfies $d^2h_m(x_c)/dx^2 < 0$):

$$(h_m)_{max} = K_m(\rho_m)_{x_c}^\alpha(c_{pm})_{x_c}^\beta(\kappa_m)_{x_c}^{1-\beta}(\mu_m)_{x_c}^{\beta-\alpha} \tag{Eq 13}$$

3. An Example of Quenching of a Circular Cylinder in a Gas Cross Flow

Several correlation equations based on experimental methods have been suggested for the examination of forced convection cross flow around a manufactured part forming a circular cylinder (Fig. 1). From the framework of engineering calculations, the correlation equation for the Nusselt number due to Zhukauskas (Ref 23):

$$Nu = CRe^\alpha Pr^\beta\left(\frac{Pr}{Pr_s}\right)^{1/4} \tag{Eq 14}$$

is widely used for both liquids and gases. Notice that the correction function, F, appearing in Eq 2 is now represented by a Prandtl number ratio in Eq 14. Here, the range of validity of Eq 14 is $1 < Re < 10^6$, $0.7 < Pr < 500$, and all the thermophysical properties are evaluated at the free stream temperature, T_∞, except Pr_s, which is evaluated at the surface temperature, T_s. If $Pr \leq 10$ (gases and common liquids), $\beta = 0.37$ whereas if $Pr \geq 10$ (oils and glycerins), $\beta = 0.36$. The values of the correlation constant C and the exponent α are taken from the companion Table 1 (Ref 23).

The exponent $\alpha = 0.4$ is associated with laminar regimes, and in contrast, the exponent α close to 0.8 is connected to turbulent regimes. Between 0.4 and 0.8, the flow is transitional.

4. Discussion of Results

The mixture of gases selected for purposes of illustration is that of helium and argon at a free stream temperature $T_\infty = 300$ K. The principal advantage of using helium in gas quenching in vacuum furnaces is the unique combination of high thermal conductivity and low density. Among gases, the thermal conductivity of helium ranks second to hydrogen, and the density of helium is lower than that of nitrogen or argon. The dependence of the density, specific heat, thermal conductivity, and viscosity of a helium and argon mixture on its composition, x, is illustrated in Fig. 2.

Table 1 lists the conditions for the cases considered covering a range of Reynolds numbers from 1 to 10^6 for comparison between laminar and turbulent cross flows. To place the heat transfer data in perspective for a mixture of gases, Fig. 3 and 4 utilize as a reference datum results for pure helium and pure argon as well. First, in Fig. 3 for an exponent a = 0.4 (laminar regime), the value of h_m/K_m shows an increasing trend with increasing concentration x until it reaches a certain value, $x_c = 0.3802$, at a plateau, and beyond this point further increase in x causes a decrease in the h_m/K_m value. Obviously, h_m/K_m is not dimensionless; see Eq 12. The corresponding values of h_m/K_m for each of the participating species are respectively, $(h/K)_{He} = 4.832$ and $(h/K)_{Ar} = 1.337$, whereas the peak value for the mixture is $h_m/K_m = 6.930$ (Table 2).

Table 1   Constants and exponents of Eq 14

Re	C	α
1 to 40	0.750	0.4
40 to 10^3	0.510	0.5
10^3 to 2×10^5	0.260	0.6
2×10^5 to 10^6	0.076	0.7

Table 2   Values of h_m/K_m for laminar and turbulent flows of pure gases and a mixture of them

α	He	Ar	He/Ar, max	x_c
0.4	4.832	1.337	6.930	0.3802
0.5	11.89	4.089	19.72	0.4314
0.6	29.27	12.49	56.53	0.4731
0.7	72.02	38.15	163.0	0.5080

In conclusion, the heat transfer data for the mixture of gases indicates significant increases in the level of heat transfer rates above those for the nonmixing cases, and numerically can be described accurately by the above calculations. The other plots in Fig. 3 (for $\alpha = 0.5$) and 4 (for $\alpha = 0.6$ and 0.7) display a repetitive pattern. The peaks h_m/K_m (proportional to the heat transfer coefficients) occur at a location where the optimal gas composition of helium and argon is shifted from $x_c = 0.3802$ to a value as high as 0.5080. As seen in Fig. 4, the peak h_m/K_m for $\alpha = 0.7$ (near turbulent regime) occurred at about $x_c = 0.5080$ and amounted to $h_m/K_m = 163$. This value is about 2.26 and 4.27 times higher than the corresponding values for pure helium and pure argon, respectively. For practical applications, it may be beneficial to inspect the outcome of this theoretical study from a different angle.

Table 3 was prepared to summarize the heat transfer enhancement ratios for the entire range of hydrodynamic parameters, namely $0.4 \leq \alpha \leq 0.7$, using as a reference each of the participating species, helium and argon. Inspection of this table reveals that the ratio $(h/K)_m/(h/K)H_e$ increases from 1.434 for $\alpha = 0.4$ to 2.263 for $\alpha = 0.7$. In contrast, the heat transfer augmentation is more pronounced for the case of argon; for instance, $(h/K)_m/(h/K)_{Ar}$ moves from 5.183 for $\alpha = 0.4$ to 4.273 for $\alpha = 0.7$.
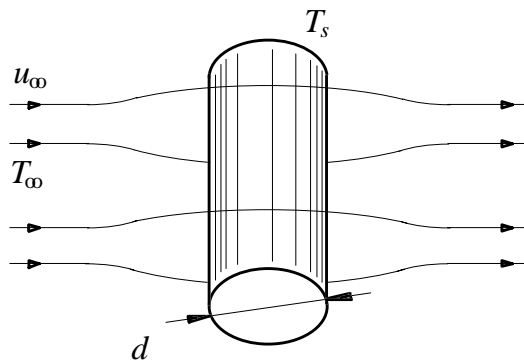

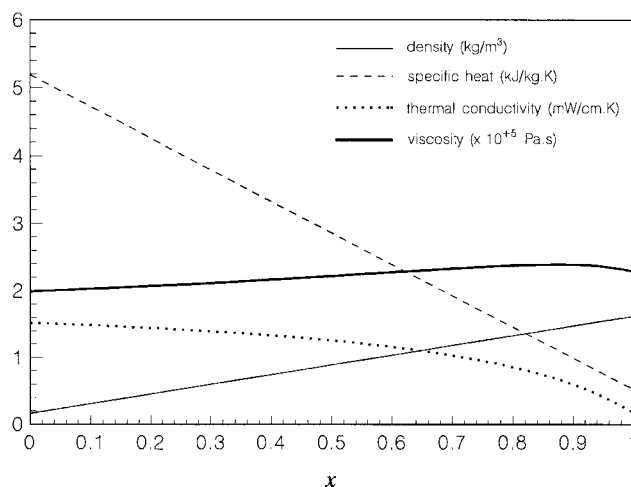**Fig. 1**   Quenching of a circular cylinder in cross flow

Fig. 2   Variation of thermophysical properties of a helium and argon gas mixture with respect to its composition x
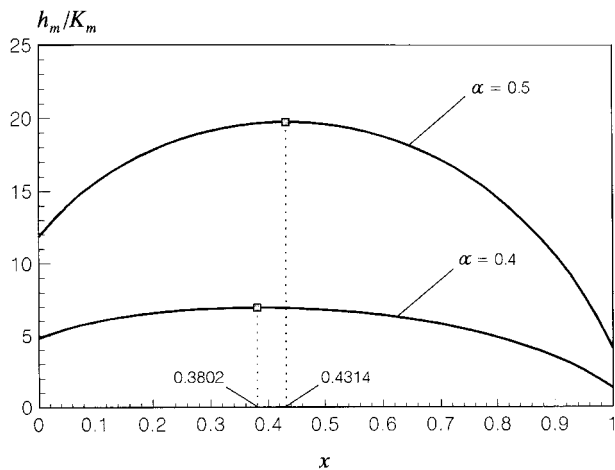
Fig. 3 Variation of h_m/K_m for a helium and argon gas mixture with respect to its composition x for $\alpha = 0.4$ and 0.5

Fig. 4 Variation of h_m/K_m for a helium and argon gas mixture with respect to its composition x for $\alpha = 0.6$ and 0.7

Table 3 Heat transfer enahncement ratios of a He and Ar gas mixture for laminar and turbulent flows

α	$(h/K)_m/(h/K)_{He}$	$(h/K)_m/(h/K)_{Ar}$
0.4	1.434	5.183
0.5	1.659	4.823
0.6	1.931	4.526
0.7	2.263	4.273

Although calculations for the heat transfer coefficients h_m were made only for a free stream temperature $T_\infty = 300$ K, the relative magnitudes of the ratios $(h/K)_m$ and $(h/K)_{He}$ were believed to be comparable for a wider range of temperature levels T_∞ by inference from the computation of similar ratios for other temperatures that are not reported.

5. Conclusions

In summary, the calculated results shown in Fig. 3 and 4 indicate that higher heat transfer levels can be attained in an environment consisting of a helium and argon gas mixture when compared to an environment consisting only of either helium or argon. Significant increases in laminar/turbulent heat transfer of approximately 140 to 230% were found for the quenching of cylindrical shapes using a helium and argon gas mixture when compared to a helium gas acting independently. With argon gas, the intensification is magnified in a more dramatic fashion, changing from 520 to 430%.

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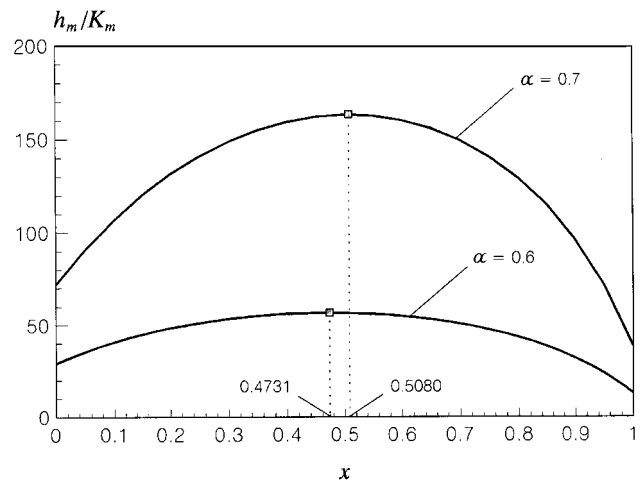5. F. Kreith and M.S. Bohn, *Principles of Heat Transfer,* 5th ed., West Publishing Co., St. Paul, MN, 1993
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