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Steady-State Evaporation Characteristics of Hydrocarbon Fuel Drops

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The influence of ambient pressure and temperature on the evaporation rates of fuel drops is examined analytically. A numerical procedure for calculating steady-state values of drop-surface temperature and evaporation constant is described. The method is used to determine the droplet evaporation characteristics of n-heptane, aviation gasoline, JP 4, JP 5, and diesel oil (DF 2) in quiescent atmospheres. Good agreement is demonstrated between calculated values of evaporation constant and corresponding published experimental results. It is shown that the pressure dependence of evaporation rates is stronger at high pressures than at low pressures. For high ambient temperatures the pressure dependence is positive; for low ambient temperatures it is negative.

Nomenclature

a,b = constants in Eq. (9)
B = transfer number
B_M = mass diffusion transfer number
B_T = thermal diffusion transfer number
c_p = specific heat at constant pressure, kJ/kg K
c_{p_g} = gas specific heat, calculated using Eq. (14)
D = drop diameter, m
k = thermal conductivity, kJ/ms K
k_g = gas thermal conductivity, calculated using Eq. (15)
L = latent heat of fuel vaporization, kJ/kg
$L_{T_{bn}}$ = latent heat of fuel vaporization at normal boiling temperature, T_{bn}, kJ/kg
$\dot{m}_F$ = rate of fuel evaporation, kg/s
M = molecular weight
n = pressure exponent of evaporation rate
P = pressure, kPa
P_{cr} = critical pressure, kPa
P_{F_s} = fuel vapor pressure at drop surface, kPa
T = temperature, K
T_b = boiling temperature, K
T_{bn} = boiling temperature at normal atmospheric pressure, K
T_{cr} = critical temperature, K
T_r = reference temperature [see Eq. (10)]
T_s = drop surface temperature, K
t = time, s
Y_i = mass fraction of i
λ = evaporation constant, m^2/s
ρ = density, kg/m^3

Subscripts

A = air
F = fuel
g = gas
r = reference value
s = value at drop surface
st = steady-state value
V = vapor
0 = initial value
∞ = ambient value

Introduction

ALTHOUGH much of the thermal energy required for power generation and domestic heating is derived from the combustion of coal and natural gas, most types of heat engines, including diesel engines, spark-ignition engines, gas turbines, liquid rockets, and ramjets, employ liquid fuels. Usually, the fuel is injected into the combustion zone in the form of a well-atomized spray. The purpose of atomization is to impart a high surface to volume ratio and thereby achieve a high rate of fuel evaporation. Evaporation is followed by mixing of the resulting fuel vapor with air, ignition of the fuel-air mixture and, finally, chemical reaction leading to the formation of combustion products. Chemical processes can limit rates of combustion in low-temperature and/or low-pressure situations, and are also important in the formation of pollutant emissions. However, in many practical combustion devices the time required for fuel evaporation is of comparable magnitude to the chemical reaction time, while in others the rate of chemical reaction is so high that the burning rate is controlled mainly by the rates at which the fuel can evaporate and mix in combustible proportions with air. Knowledge of evaporation rates is thus of prime importance to the design of liquid-fueled combustors. Moreover, evaporation processes seem likely to assume even greater consequence in the future, in view of the trend toward "alternative fuels," most of which are less volatile than the light distillate fuels which have been readily available in the past.

Estimations of the evaporation rates and burning times of fuel drops are simple and straightforward if the appropriate value of λ, the evaporation constant, is known. Even if no experimental data are available it is still possible to calculate λ for any given value of drop surface temperature T_s. The main difficulty lies in determining T_s. Under certain conditions, such as the combustion of fuel drops in high-temperature flames, it is often sufficiently accurate to equate T_s to the boiling temperature of the fuel T_b. However, for low-temperature flames, or for fuel evaporation in air at low ambient temperature, this assumption would incur significant error. Another potential source of serious error in the calculation of λ stems from the shortage of data on the relevant physical properties of commercial fuels and their vapors at the levels of pressure and temperature of most practical interest.

The objective of this study is to provide calculated values of T_s and λ, for several fuels of interest for the gas turbine, namely, aviation gasoline, JP 4, JP 5, and diesel oil (DF2). Since many previous studies on evaporation have utilized n-

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heptane, values of λ for this fuel have also been determined. The calculated values of λ are used to examine the influence of ambient gas pressure and temperature on drop evaporation rates. Although the analysis is confined to single drops, it is felt that the results obtained have direct relevance and significance to the combustion of fuel sprays.

Steady-State Evaporation

The development of drop evaporation theory has been motivated largely by the needs of the aero gas turbine and the liquid propellant rocket engine. Following Godsave[1] and Spalding[2] the approach generally used is to assume a spherically symmetric model of a vaporizing drop in which the rate-controlling process is that of molecular diffusion.

Consider the hypothetical case of a pure fuel drop that is suddenly immersed into gas at high temperature. Following Faeth,[3] the ensuing evaporation process proceeds according to the sketch provided in Fig. 1. At normal fuel injection temperatures the concentration of fuel vapor at the liquid surface is low, and there is little mass transfer from the drop in this initial stage. Under these conditions the fuel drop heats up exactly like any other cold body when placed in a hot environment. Due to the limited heat conductivity of the fuel, the temperature inside the drop is not uniform, but is cooler at the center of the drop than at the liquid surface.

As the liquid temperature rises so also does the partial pressure and concentration of fuel vapor at the surface. This increases the rate of dispersion of fuel vapor away from the droplet which has two effects: 1) a larger proportion of the heat transferred to the drop is needed to furnish the heat of vaporization of the liquid, and 2) the outward flow of fuel vapor impedes the rate of heat transfer to the drop. This tends to diminish the rate of increase of the surface temperature so that the level of temperature within the droplet becomes more uniform. Eventually, a stage is reached where all of the heat transferred to the droplet is used as heat of vaporization and the droplet temperature stabilizes at its "steady-state" or "wet bulb" temperature.

The term "steady-state" is, in fact, a misnomer when applied to drop evaporation or drop combustion, because a fuel drop rarely attains a steady state during its lifetime. This is especially true for multicomponent fuel drops, which may contain several different petroleum compounds, each possessing its own individual physical and chemical properties. Nevertheless, for most light distillate fuel oils it is convenient to consider a quasisteady gas phase which embodies the main features of the mass and thermal diffusion processes, and which allows mass evaporation rates and drop lifetimes to be estimated to a reasonable level of accuracy.

During its lifetime the diameter D of an evaporating drop may be related to its initial diameter D_0 by the equation

$$D_0^2 - D^2 = \lambda t \tag{1}$$

where λ is the evaporation constant as defined by Godsave.[1] This definition of λ allows the rate of fuel evaporation to be expressed as

$$\dot{m}_F = (\pi/4)\rho_F \lambda D \tag{2}$$

Following Spalding[2] the steady-state evaporation of a single fuel drop is given by

$$\dot{m}_F = 2\pi D(k/c_p)_g \ln(1+B) \tag{3}$$

Equating Eqs. (2) and (3) gives

$$\lambda_{\mathrm{st}} = \frac{8\ln(1+B)}{\rho_F (c_p/k)_g} \tag{4}$$

This equation allows λ_{st} to be calculated from a knowledge of the fluid properties ρ_F, c_{p_g}, and k_g and the transfer number B.

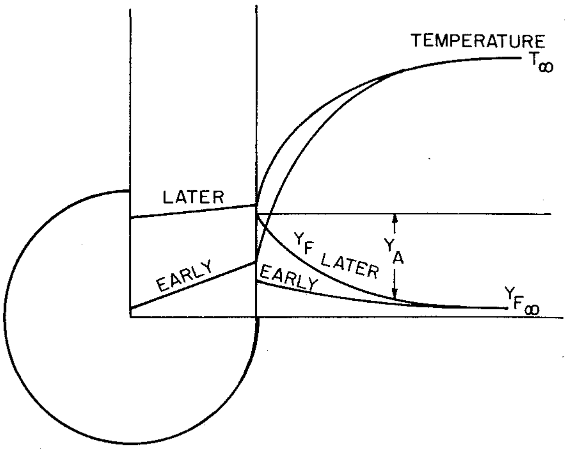

Fig. 1 Variation of temperature and gas concentration during droplet evaporation.[3]

Mass Transfer Number

If conditions are such that evaporation rates are controlled by mass diffusion processes, then B in Eq. (3) should be replaced by B_M to give

$$\dot{m}_F = 2\pi D(k/c_p)_g \ln(1+B_M) \tag{5}$$

B_M is defined as $(Y_{F_s} - Y_{F_\infty})/(1 - Y_{F_s})$. Usually Y_{F_∞} is zero. Hence,

$$B_M = Y_{F_s}/(1 - Y_{F_s}) \tag{6}$$

Now

$$Y_{F_s} = \frac{P_{F_s} M_F}{P_{F_s} M_F + (P - P_{F_s}) M_A} \tag{7}$$

$$Y_{F_s} = \left[1 + \left(\frac{P}{P_{F_s}} - 1\right)\frac{M_A}{M_F}\right]^{-1} \tag{8}$$

where P_{F_s} is the fuel vapor pressure at the drop surface; P the ambient pressure, which is the sum of the fuel vapor pressure and the air partial pressure at the droplet surface; and M_F and M_A the molecular weights of fuel and air, respectively.

For any given value of surface temperature, the vapor pressure is readily estimated from the following modified form of the Clausius-Clapeyron equation.[4]

$$P_{F_s} = \exp[a - b/(T_s - 43)] \tag{9}$$

Values of a and b for the fuels of interest are listed in Table 1.

The accuracy of Eq. (5) for calculating rates of fuel evaporation is very dependent on the choice of values of k_g and c_{p_g}. According to Hubbard et al.,[5] best results are obtained using the one-third rule of Sparrow and Gregg,[6] where average properties are evaluated at the following reference temperatures and compositions.

$$T_r = T_s + \tfrac{1}{3}(T_\infty - T_s) \tag{10}$$

$$Y_{F_r} = Y_{F_s} + \tfrac{1}{3}(Y_{F_\infty} - Y_{F_s}) \tag{11}$$

where T is temperature, Y_F the mass fraction of fuel vapor, and subscripts r, s, and ∞ refer to reference, surface, and ambient conditions. If the fuel concentration at an infinite distance from the drop is assumed to be zero, then Eq. (11) becomes

$$Y_{F_r} = \tfrac{2}{3} Y_{F_s} \tag{12}$$

and

$$Y_{A_r} = 1 - Y_{F_r} = 1 - \tfrac{2}{3} Y_{F_s} \tag{13}$$

Equations (10-13) are used to calculate the reference values of the relevant physical properties of the vapor-air mixture that comprises the environment of an evaporating drop. For example, the reference specific heat at constant pressure is obtained as

$$c_{p_g} = Y_{A_r}(c_{p_A} \text{ at } T_r) + Y_{F_r}(c_{p_v} \text{ at } T_r) \tag{14}$$

The reference value of thermal conductivity is estimated in a similar manner as

$$k_g = Y_{A_r}(k_A \text{ at } T_r) + Y_{F_r}(k_v \text{ at } T_r) \tag{15}$$

Heat Transfer Number

Similar considerations to those just outlined, but based on considerations of conductive and convective heat fluxes across a thin shell surrounding the evaporating drop, lead to the following expression for heat transfer number:

$$B_T = [c_{p_g}(T_\infty - T_s)]/L \tag{16}$$

where L is the latent heat of fuel vaporization corresponding to the fuel surface temperature T_s.

B_T denotes the ratio of the available enthalpy in the surrounding gas to the heat required to evaporate the fuel. As such, it represents the driving force for the evaporation process. Where heat transfer rates control the evaporation, the rate of fuel evaporation for a Lewis number of unity is obtained as

$$\dot{m}_F = 2\pi D(k/c_p)_g \ln(1+B_T) \tag{17}$$

Under steady-state conditions $B_M = B_T = B$, and either Eq. (5) or Eq. (17) may be used to calculate the rate of fuel evaporation. The advantage of Eq. (5) is that it applies under all conditions, including the transient state of droplet heat up. On the other hand, Eq. (17) is easier to evaluate when the ambient gas temperature is significantly higher than the fuel surface temperature T_s, in which case it is sufficiently accurate to replace T_s by the boiling temperature of the fuel.

Calculation of Steady-State Values of T_s and λ

One method of calculating λ_{st}, the evaporation constant under steady-state conditions, is by following the graphical procedure as described by Spalding[7] and Kanury.[8] The basic

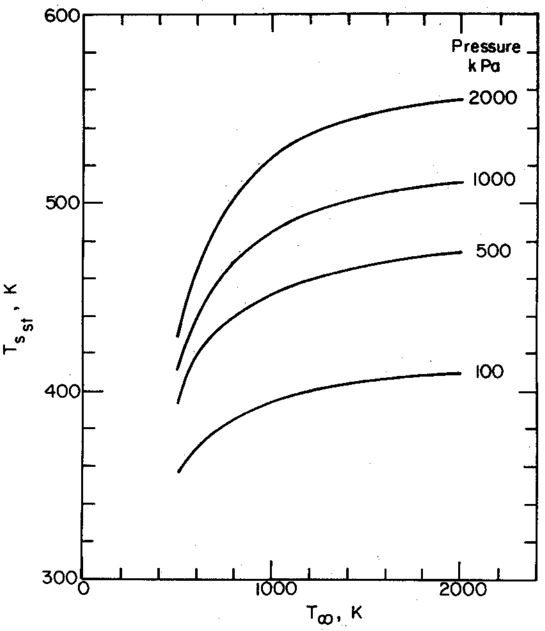

Fig. 2 Influence of ambient pressure and temperature on steady-state drop surface temperature for JP 4.

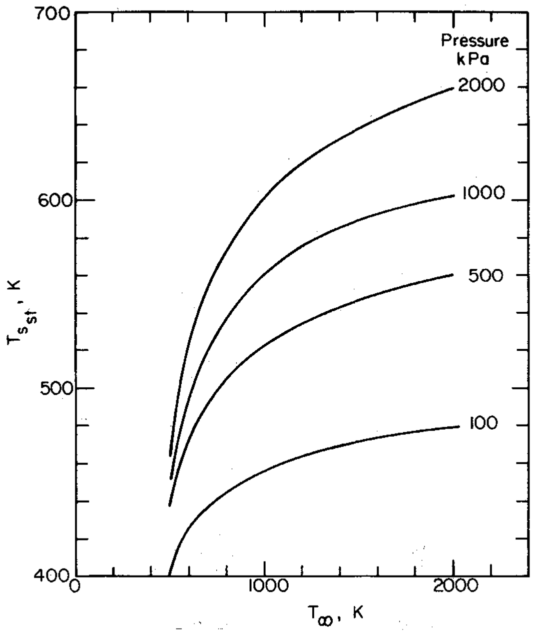

Fig. 3 Influence of ambient pressure and temperature on steady-state drop surface temperature for JP 5.

Table 1 Some relevant thermophysical properties

	n-Heptane	Aviation gasoline	JP 4	JP 5	DF 2
T_{cr}, K	540.17	548.0	612.0	684.8	725.9
P_{cr}, kPa	2736	6205	3654	2275	2089
$L_{T_{bn}}$, kJ/kg	317.8	346	292	266.5	254
Molecular mass	100.16	108.0	125.0	169.0	198.0
Density, kg/m^3	687.8	724	773	827	846
T_{bn}, K	371.4	333	420	495.3	536.4
C_{ex}, K^{-1}	0.000715	0.000645	0.000557	0.000485	0.00046
a in Eq. (9) for $T > T_{bn}$	14.2146	14.1964	15.2323	15.1600	15.5274
a in Eq. (9) for $T < T_{bn}$	14.3896	13.7600	15.2323	15.1600	15.5274
b in Eq. (9) for $T > T_{bn}$, K	3151.68	2777.65	3999.66	4768.77	5383.59
b in Eq. (9) for $T < T_{bn}$, K	3209.45	2651.13	3999.66	4768.77	5383.59

idea is to plot graphs of B_M and B_T against T_s until the two curves intersect. The point of intersection of the two lines defines B and $T_{s_{st}}$. The corresponding value of λ_{st} is then obtained from Eq. (4). The advantage of this method is that it provides a useful pictorial representation of the variation of the thermal and mass diffusion driving forces with temperature. Its main drawback is that it is not very accurate, especially when the B_M and B_T lines intersect each other at a narrow angle. Much greater accuracy is possible with the numerical method described next.

Numerical Method

At the steady-state condition $B_M = B_T$, assuming a Lewis number of unity. Thus, from Eqs. (6) and (16)

$$\frac{Y_{F_s}}{1-Y_{F_s}} = \frac{c_{p_g}(T_\infty - T_{s_{st}})}{L} \tag{18}$$

Substituting for Y_{F_s} from Eq. (8) gives

$$\frac{P}{P_{F_s}} - \frac{M_F}{M_A}\frac{L}{c_{p_g}(T_\infty - T_{s_{st}})} - 1 = 0 \tag{19}$$

In any given calculation, P, M_F, M_A, and T_∞ are known at the outset. All the other terms are functions of T_s. Thus

$$P_{F_s} = \exp[a - b/(T_s - 43)] \text{ kPa} \tag{9}$$

and

$$L = L_{T_{bn}}\left[\frac{T_{cr} - T_s}{T_{cr} - T_{bn}}\right]^{0.38} \text{kJ/kg} \tag{20}$$

from Refs. 9 and 10. Values of a, b, T_{cr}, T_{bn}, and $L_{T_{bn}}$ are contained in Table 1.

For any specified value of T_s, P_{F_s} and L are calculated from Eqs. (9) and (20), respectively. The only remaining unknown quantity in Eq. (19) is c_{p_g}. This is calculated using Eq. (14) in which the specific heat of the fuel vapor is given by

$$c_{p_v} = (0.363 + 0.000467T)(5 - 0.001\rho_{F_0}) \text{ kJ/kg K} \tag{21}$$

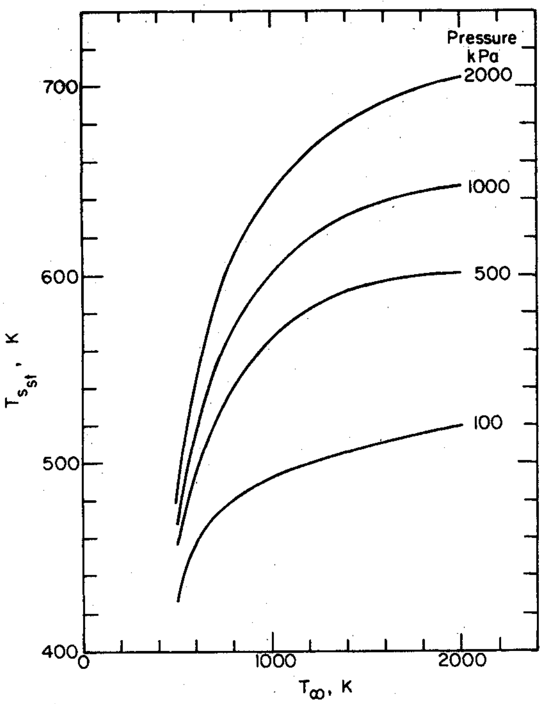

Fig. 4 Influence of ambient pressure and temperature on steady-state drop surface temperature for DF 2.

where ρ_{F0} is the fuel density in kg/m³ at 288.6 K. The value of c_{pA} at temperature T_r and pressure P may be obtained from standard charts, e.g., Ref. 11.

If the selected value of T_s is lower than $T_{s_{st}}$ the left-hand side of Eq. (19) will have a negative value. The value of T_s should then be raised in small steps until the left-hand side of Eq. (19) becomes close to zero. This procedure allows $T_{s_{st}}$ to be determined to any desired degree of accuracy. In the present study it has been used to calculate values of $T_{s_{st}}$ for n-heptane, aviation gasoline, JP 4, JP 5, and DF 2 for ambient temperatures up to 2000 K and pressures up to 2 MPa (approximately 20 atm). The results for JP 4, JP 5, and DF 2 are shown plotted in Figs. 2-4.

Having determined $T_{s_{st}}$, the corresponding value of B is then derived using Eqs. (6), (8), and (9). The additional properties needed to calculate λ_{st} are ρ_F and k_g. The variation of fuel density with temperature is given by (see Appendix)

$$\rho_{F_T} = \rho_{F_{288.6}}[1 - 1.8C_{ex}(T - 288.6) - 0.090(T - 288.6)^2 \div (T_{cr} - 288.6)^2] \text{ kg/m}^3 \tag{22}$$

Values of the expansion coefficient C_{ex}, for the fuels covered in this study, are listed in Table 1.

The thermal conductivity k_g is obtained by inserting the corresponding values of k_A and k_V into Eq. (15). Data on k_A are readily available (see, Ref. 11, for example) but information on k_V is quite sparse. It is shown in the Appendix that the thermal conductivity of fuel vapor is given to a reasonable level of accuracy by the expression

$$k_{V_T} = 10^{-6}[13.2 - 0.0313(T_{bn} - 273)](T/273)^n \text{ kg/ms K} \tag{23}$$

where

$$n = 2 - 0.0372(T/T_{bn})^2 \tag{24}$$

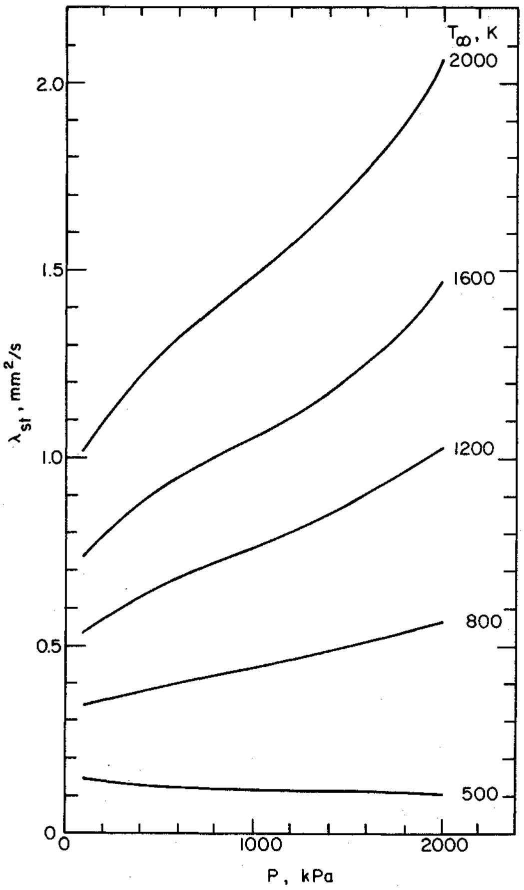

Fig. 5 Influence of ambient pressure and temperature on steady-state evaporation constant for n-heptane.

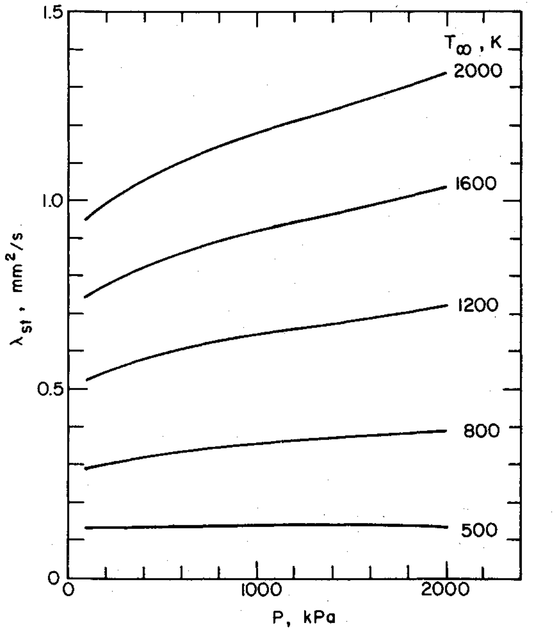

Fig. 6 Influence of ambient pressure and temperature on steady-state evaporation constant for aviation gasoline.

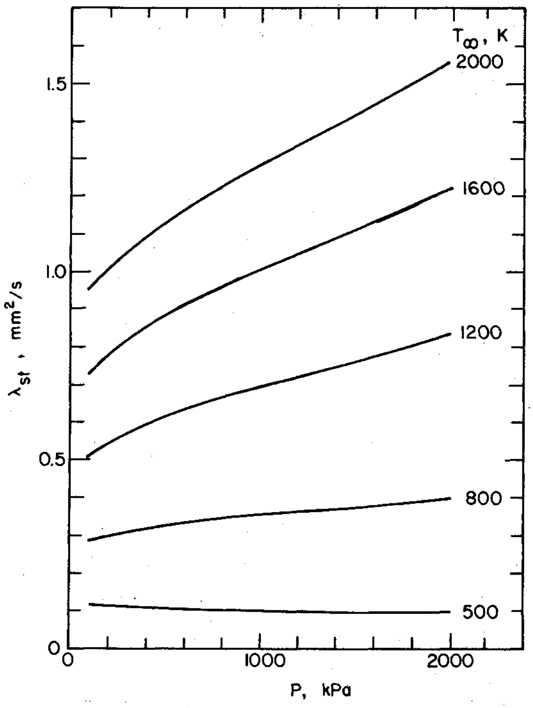

Fig. 7 Influence of ambient pressure and temperature on steady-state evaporation constant for JP 4.

Calculated values of λ_{st} from Eq. (4) for all fuels, over wide ranges of pressure and ambient temperature, are shown plotted in Figs. 5-9. Unfortunately, the paucity of experimental data on λ_{st} for commercial fuels at pressures other than normal atmospheric pressure virtually prohibits any worthwhile comparison between experiment and calculation. However, where comparison can be made, the result is encouraging, as illustrated in Table 2. This table shows calculated values of λ_{st} for n-heptane, gasoline, and DF 2 at a temperature of 2000 K and normal atmospheric pressure listed alongside the corresponding measured values for burning drops at the same pressure, due to Godsave.[1] The level of agreement between the calculated and measured values of λ_{st} is clearly very satisfactory.

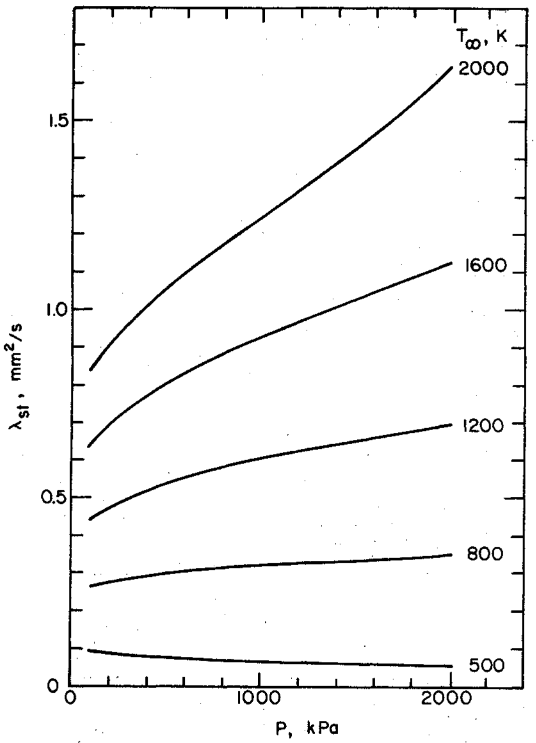

Fig. 8 Influence of ambient pressure and temperature on steady-state evaporation constant for JP 5.

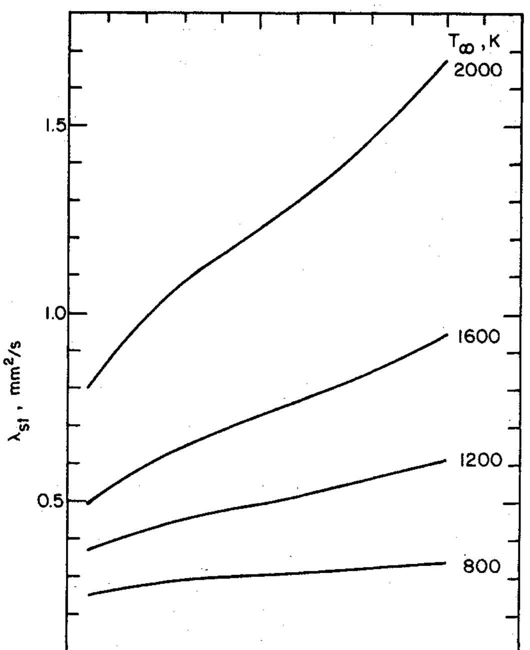

Fig. 9 Influence of ambient pressure and temperature on steady-state evaporation constant for DF 2.

Table 2 Comparison of calculated and experimental values of λ_{st}

Fuel	Calculated, mm²/s	Experimental,[1] mm²/s
n-Heptane	0.979	0.97
Gasoline	0.948	0.99
DF 2	0.802	0.79

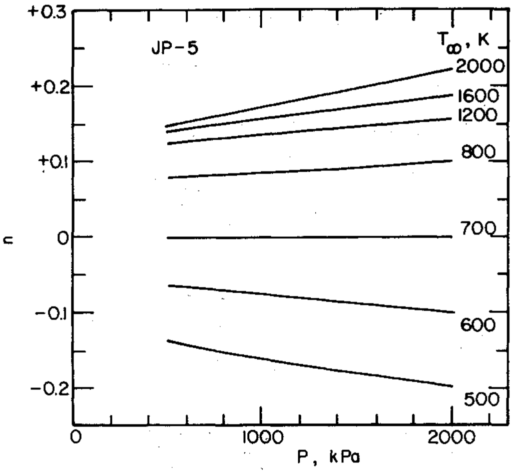

Fig. 10 Effect of ambient pressure and temperature on the pressure dependence of evaporation rates for JP 5.

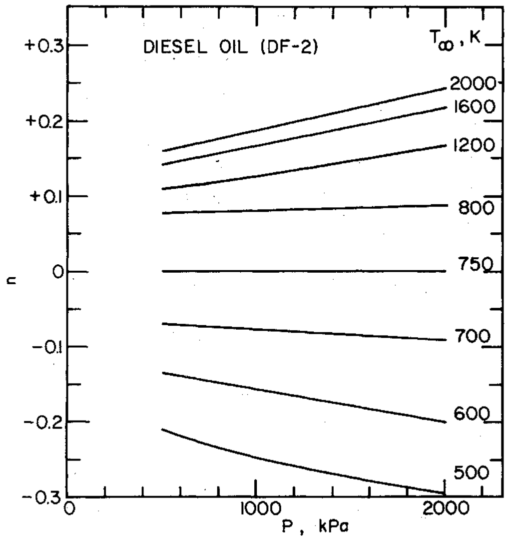

Fig. 11 Effect of ambient pressure and temperature on the pressure dependence of evaporation rates for DF 2.

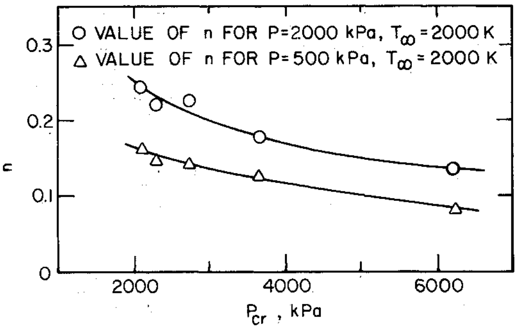

Fig. 12 Variation of pressure exponent n with critical fuel pressure.

It should be noted that the values of λ_{st} contained in Figs. 5-9 are for quiescent mixtures only. For the evaporation of fuel drops in flowing streams, the effects of convection are readily accommodated by the use of correction factors of the form $(1+CRe^xPr^y)$, as discussed by Odgers[12] and Faeth.[3]

Influence of Pressure and Temperature on Evaporation Rates

The graphs drawn in Figs. 5-9 show clearly that evaporation rates increase markedly with increase in ambient temperature. The effect of pressure on evaporation rates is more complex. The figures show that λ_{st} increases with pressure when the ambient temperature is high (>800 K) and declines with increase in pressure when the ambient temperature is low (<600 K). Between 600 and 800 K evaporation rates are sensibly independent of pressure. If the pressure dependence of λ_{st} is expressed in the form

$$\lambda_{st}\alpha P^n \tag{25}$$

it is found that, over the range of pressures and temperatures considered, the value of n varies between ± 0.25. At the highest levels of ambient temperature, corresponding to burning conditions, Figs. 10 and 11 show for JP 5 and DF 2, respectively, that n lies between 0.15 and 0.25, which is in fair agreement with the value of 0.25 as determined experimentally by Diederichsen and Hall[13] for suspended burning fuel drops over a pressure range from 1 to 20 atm.

For high ambient temperatures, around 2000 K, the pressure exponent n correlates well with critical fuel pressure, as illustrated in Fig. 12. This figure also shows that the dependence of evaporation rates on pressure decreases with increase in critical fuel pressure.

Appendix

Some of the thermophysical properties needed to calculate evaporation rates are readily available in the literature, such as, for example, the specific heat and thermal conductivity of air. Other important properties, however, especially those relating to fuel and fuel vapor, are most difficult to come by. The results obtained by different workers are sometimes conflicting and tend to cover only a narrow range of temperatures. In order to alleviate this situation an attempt has been made to extract the most reliable experimental data in

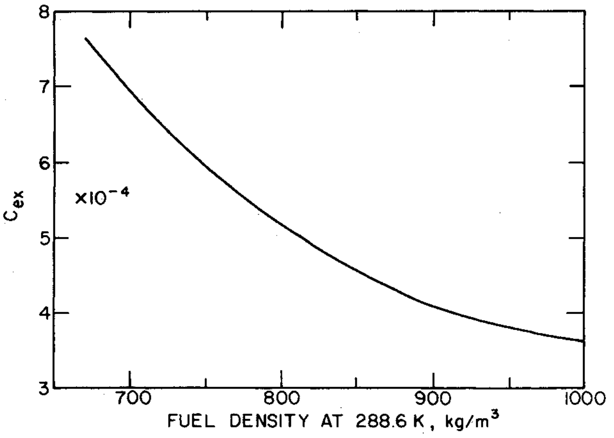

Fig. A1 Effect of fuel density on coefficient of thermal expansion.[14]

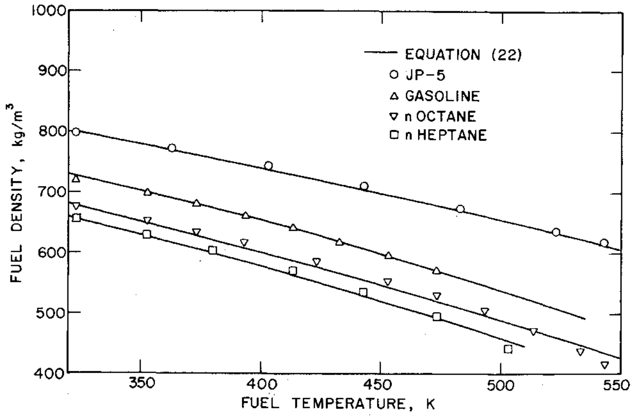

Fig. A2 Comparison of predicted values of fuel density with measured values from Ref. 15.

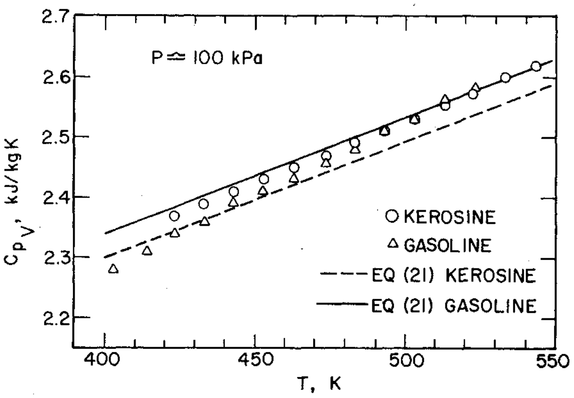

Fig. A3 Correlation of experimental data on the specific heat of fuel vapor.

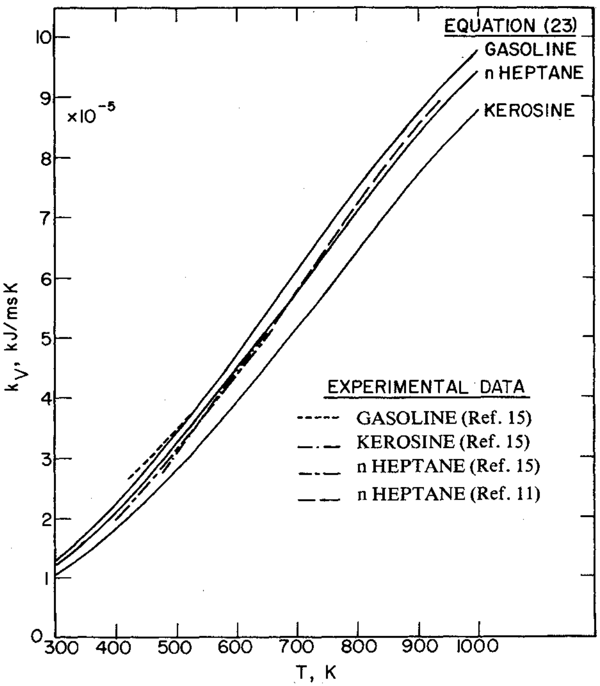

Fig. A4 Correlation of experimental data on the thermal conductivity of fuel vapor.

the literature and to express the variation of each key property with temperature in the form of equations which lend themselves to computer calculations.

Fuel Density

The variation of fuel density with temperature is described with fair accuracy by Eq. (22). Values of C_{ex} are listed in Table 1 and shown plotted as a function of fuel density at 288.6 K in Fig. A1 from Ref. A2. The close level of agreement between the predictions of this equation and the experimental data quoted in Ref. 15 is shown in Fig. A2.

Specific Heat of Fuel Vapor

The variation of specific heat of hydrocarbon fuel vapor with temperature is described by relationship (21), where ρ_{F0} is the fuel density at a temperature of 288.6 K. Equation (21) is shown plotted in Fig. A3 alongside experimental data for gasoline and kerosine from Ref. 15.

Thermal Conductivity of Fuel Vapor

The influence of temperature on the thermal conductivity of fuel vapor is illustrated in Fig. A4. This figure shows experimental data from Refs. 11 and 15 plotted alongside graphs of Eqs. (23) and (24).

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