

New Correlations for Leidenfrost and Nukiyama Temperatures with Gas Pressure - Application to Liquid Film Boiling Simulation

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Abstract

Among the physical processes occurring when a liquid film is formed on the surface of the combustion chamber of a direct injection engine, heat transfer and phase changes are of primary importance. The vaporization rate of the liquid film is not only a function of the wall temperature but it is strongly affected by the gas pressure variation inside the combustion chamber. Indeed, processes occurring during the piston expansion stroke are similar to those occurring when increasing the wall temperature T_w . In this last case, one may distinguish four regimes of vaporization in the literature [1-3], which can be classified according to the extent of superheating of the wall and using as limits for these regimes, the saturation temperature T_{sat} , the Nukiyama temperature T_N and the Leidenfrost temperature T_L . The two last critical temperatures are usually determined experimentally from the lifetime curve of a droplet. This curve is obtained by measuring the total time that it takes a droplet to completely evaporate after it has been gently deposited on a hot wall [4-6]. In this paper, a particular attention has been made concerning the estimation of Leidenfrost and Nukiyama temperatures. A new correlation is suggested for their calculation as a function of the ambient gas pressure. Several curves of lifetime of rather bulky droplets deposited on a hot surface under various conditions and chosen among those which are available in the recent literature have been used for the validation of the suggested correlation. The numerical results obtained in conjunction with of the liquid film boiling (LFB) model [7] show that the orders of magnitude and the tendencies observed experimentally are well respected. Particularly, these models reproduce well the progressive disappearance of the Leidenfrost regime observed under sufficiently high gas pressures in several previously published experiments.

Introduction

In automobile engines, the technology of direct injection in the combustion chamber is widely used. Indeed, Direct injection technology allows to control the consumption of combustible and the pollutant emissions which is difficult in port fuel injection engines. Besides, the pressures used in the injection systems are increased more and more to improve the spray atomization, mixture preparation and combustion. In these conditions, liquid spray may impinge the internal surface of the combustion chamber. This interaction of spray with the wall involves different physical phenomena according to the conditions of impact (speed of the droplets, temperature of the wall, roughness of the surface, etc) and of the gas pressure in the combustion chamber [1, 8-13].

In Diesel engines for instance, the fuel injection often occur during the course of the compression stroke of fresh gases. As the saturation temperature of fuel oil increases with the gas pressure, the impact of spray on the wall leads in most cases to the formation of a liquid film. The latter evaporates rather slowly and may even remain after the combustion [14]. In the course of the expansion stroke, the saturation temperature of fuel oil diminishes with gas pressure to the point of attaining a value lower than the wall temperature and consequently leading to the boiling of the liquid film. Furthermore, the Leidenfrost and Nukiyama temperatures diminish as well during the expansion stroke leading to a continuous variation of the boiling regimes. Very few works in the literature were dedicated to model these phenomena for shallow liquid films. Indeed, although the prediction of the Leidenfrost and Nukiyama temperatures is currently important in many engineering applications, there seems to be a considerable uncertainty in the literature concerning the numerical values of the Leidenfrost and Nukiyama temperatures. For example, Xiong and Yuen [15] reported up to 30 K of uncertainty for water on stainless steel. Table 1 displays the variations in the Leidenfrost temperature for water on stainless steel which have been reported in the literature. The uncertainties of the experimental values of Leidenfrost temperature may be due to difference in the size of liquid volume V_f (i.e. diameter d_0 of the droplet), method of drop deposition, amount of liquid subcooling T_b , solid thermal properties, surface material and finish, presence of impurities, and gas pressure. Moreover, with the knowledge of the author, no model exists in the literature for the modelling the effect of pressure on the Nukiyama temperature. The first objective of this paper is to present previously developed models that attempt to predict Leidenfrost point (LFP) temperature. Next, a new correlation is suggested for the cal-

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ulation of the Leidenfrost and Nukiyama temperatures as function of the gas pressure. Finally, available experimental lifetime curves of droplets having diameters larger than 2 mm and which were deposited on a hot wall are used to validate the suggested new correlation for different ambient gas pressures [16].

Table 1. Summary of Leidenfrost temperature for water on Stainless steel as reported in the literature (cited references can be found in [11]) at atmospheric pressure ($p=101.3kPa$).

| Reference | T_L [K] | Notes |
|-----------------------------|-----------|---|
| Tamura & Tanasawa (1959)[5] | 575 | |
| Godleski & Bell (1966) | 593 | |
| Gottfried et al. (1966) | 553 | |
| Patel & Bell (1966) | 578 | $0.05 < V_f < 10$ ml |
| Baumeister et al. (1970) | 578, 525 | $d_{\theta}=0.39$ & 2.25 mm |
| Emmerson (1975)[17] | 555 | LFP also given for pressures of 210, 313,420, and 525 kPa |
| Xiong & Yuen (1991)[15] | 553-583 | |

Main previous LFP models

In the literature, several studies have reported various correlations for predicting the LFP temperature T_L . The Spiegler’s model is the simplest one. Spiegler et al. [18] assumes that T_L is a thermodynamic state property of the fluid which corresponds to the spinodal or maximum superheat temperature of the liquid. Using the mechanical stability condition $\left(\frac{\partial P}{\partial v}\right)_T = 0$ and Van der Waals equation of state for the fluid, they arrived to the following expression for T_L when $p \ll p_c$:

$$T_L = \frac{27}{32} T_c \tag{1}$$

where T_c is the critical temperature of the fluid.

Next, Baumeister and Simon [19] included to Equation (1) corrections in order to account for the thermal properties of the heated surface and wetting characteristics of the liquid-solid system. They obtained the following semi-empirical expression:

$$T_L = T_f + \frac{\frac{27}{32} T_c \left\{ 1 - \exp \left[-0.016 \left[\frac{\left(\frac{\rho_s}{A_s} \right)^{4/3}}{\sigma_f} \right] \right]^{1/3} \right\} - T_f}{\exp \left(\frac{3.066E6}{k_s \rho_s C p_s} \right) \cdot \operatorname{erf} \left(\frac{1758}{\sqrt{k_s \rho_s C p_s}} \right)} \tag{2}$$

where σ_f is vapour-liquid surface tension and k_s , ρ_s , $C p_s$ and A_s are the thermal conductivity, the density, the specific heat at constant pressure and the atomic weight of surface material respectively.

For fluid at higher pressure up to the critical pressure p_c , Lienhard [20] suggested the following T_L correlation:

$$T_L = T_c \left[0.905 + 0.095 \left(\frac{T_{sat}}{T_c} \right)^8 \right] \quad (3)$$

Suggested Nukiyama and Leidenfrost temperatures correlations with gas pressure

Temple-Pediani [21] and more recently Stanglmaier et al. [16] have studied the effect of the ambient gas pressure on the evaporation of a droplet posed on a hot wall. Temple-Pediani [21] noted the absence of the vapor cushion which is the main characteristic of the Leidenfrost regime, if the gas pressure exceeds the critical pressure of the fluid. He explained the absence of the vapour cushion by the fact that the vapour pressure becomes insufficient to raise the liquid far from the wall. In other words, an increase in the gas pressure leads to a reduction of the rate of vaporization. These observations have been recently confirmed by Stanglmaier et al. [16]. Their experiments showed that the Leidenfrost regime is less and less important as the gas pressure is increased. In the liquid film boiling (LFB) model [7], the reduction of the thickness of the vapour cushion δ_v as a function of the gas pressure p has been expressed by the following relationship:

$$\delta_v = \frac{10^6}{p^2} \quad (4)$$

This relationship has been obtained by assuming that $(\delta_v \cdot p^2)$ keeps a constant value when the ambient pressure changes. In addition, a shift of the lifetime curve towards the right side (i.e. towards the high wall temperatures) has been also observed when the gas pressure is increased. This shift involves T_{sat} , T_N and T_L at the same time. On the one hand, the variation of the saturation temperature with pressure can be easily obtained using the Clausius-Clapeyron formula, at least for single-component liquid. On the other hand, the shifts of T_N and T_L must be formulated according to available experimental observations. An interesting experimental work was recently published by Fardad and Ladommatos [22]. They showed that $(T_L - T_N)$ is very close to $(T_N - T_{sat})$ for several liquids including typical gasoline and Diesel fuels. In addition, these differences decrease when the gas pressure is increased. Moreover, $(T_L - T_N)$ and $(T_N - T_{sat})$ seem to be constant when the gas pressure is decreased under atmospheric pressure. These behaviors have been formulated in [7] by the following expressions:

$$T_{cr} = T_{sat} + \Delta T \quad (5)$$

where T_{cr} represents either T_N or T_L and ΔT is calculated according to the gas pressure p in the following way:

$$\Delta T = \begin{cases} T_{cr|1bar} - T_b & \text{if } (p \leq 1 \text{ bar}) \\ \frac{(T_{cr|1bar} - T_b) - A}{T_c - T_b} (T_c - T_{sat}) + A & \text{if } (p > 1 \text{ bar}) \end{cases} \quad (6)$$

where T_b and T_c are respectively, the normal boiling temperature and the critical temperature. For the high pressure case, the value of ΔT is assumed to tend linearly towards the value $A = \text{Max}(1, T_{cr|1bar} - T_c)$ when the gas pressure tends towards the critical pressure. It is worth to recall that the values of $T_{cr|p=1bar}$ (i.e. T_N and T_L at $p=1bar$) are supposed to be provided by lifetime curves of fuel droplets obtained experimentally in conditions close to those of the target application. Table 2 gives the T_N and T_L data which have been obtained by Stanglmaier et al. [16] at atmospheric pressure.

Table 2. Nukiyama and Leidenfrost Temperatures obtained at atmospheric pressure. The experimental conditions given in the original papers are also recalled.

| Liquid | T_N , K | T_L , K | Reference and experimental conditions |
|------------|-----------|-----------|--|
| iso-octane | 395 | 463 | [16] : Impact of drops ($d_0 = 2$ mm) on aluminium heated plate |

New correlations validation

The validation of the suggested correlations (5)-(6) is carried out mainly on the basis of experimental data resulting from the article of Stanglmaier et al. [16], referred to below as SRM. In these experiments, the lifetime durations of rather bulky droplets ($d_0 > 2 \text{ mm}$) deposited on a hot surface were measured under various conditions. Droplets of n-pentane, n-decane and isooctane have been studied by SRM. Lifetime curves which were obtained for several ambient pressures in the isooctane case will be used in the following, for the assessment of the suggested correlations.

Initialization method of the liquid film

Once deposited gently on the wall, a droplet spreads and forms a liquid film of a maximum diameter (denoted D_{max}) up to 3 to 5 times the initial diameter d_0 depending on the value of the droplet Weber number [22-24]. In this work, we assumed:

- The droplet after impact takes the form of a cylinder with radius \bar{r}_f and height \bar{h}_f .
- The vaporized mass before the droplet takes the cylindrical form is negligible relatively to the mass of the droplet.

In order to calculate \bar{r}_f and \bar{h}_f , we first used the model of Nagaoka et al. [25] which can be summarized by the following system of equations:

$$\begin{aligned} r_f^3 &= \frac{4r_0^3 \sin^3 \phi}{2 - 3 \cos \phi + \cos^3 \phi} \\ \cos \phi &= \frac{1 - (h_{f \max} / r_f)^2}{1 + (h_{f \max} / r_f)^2} \\ \frac{h_{f \max}}{r_f} &= \frac{0.0354}{E_0^{0.51}} \quad \text{and} \quad E_0 = \frac{4g(\rho_f - \rho_g)}{\sigma_f} \end{aligned} \quad (7)$$

while denoting $r_0 = d_0/2$ and $h_{f \max}$ the height of the cylinder which has a radius $r_f = D_{max}/2$ (see the diagram of Figure 1 for the notations). Then, one can evaluate the minimal height by $h_{f \min} = \frac{V_0}{\pi r_f^2}$ with $V_0 = \frac{4}{3} \pi r_0^3$. Finally,

\bar{h}_f and \bar{r}_f are obtained by:

$$\bar{h}_f = \frac{h_{f \max} + h_{f \min}}{2} \quad \text{and} \quad \bar{r}_f = \sqrt{\frac{V_0}{\pi \bar{h}_f}} \quad (8)$$

In, we summarise the initial characteristics of liquid films corresponding to the isooctane droplets used by SRM [16]. The ratio of the maximum spreading radius to the initial droplet radius just prior to impact, \bar{r}_f / r_0 is more or less equal to 4. This large value may indicate that SRM has probably used relatively large Weber numbers [23]. The experimental Weber numbers were not given in their article.

Table 3. Initial conditions for the calculations of lifetime durations of isoctane droplets

| Parameters | isooctane |
|-------------------------|----------------------|
| V_0 | 5 μl |
| r_0 | 1 mm |
| \bar{r}_f / r_0 | 4.28 |
| $A_f = \pi \bar{r}_f^2$ | 57.4 mm ² |
| \bar{h}_f | 87 μm |

Results and Discussion

The suggested correlations for T_N and T_L have been used in conjunction with the LFB model [7]. Figure 2 compares the numerical results with the experiments of SRM [16]. One may note that the dependence of the temperatures of Nukiyama and Leidenfrost with the pressure is correctly predicted. In addition, the numerical results reproduce well the progressive disappearance of the Leidenfrost regime observed in previous experiments [16, 21]. It is however worth noting some dissension between the experimental and numerical curves, in particular at the beginning of the nucleate boiling regime (with low pressure, $p=50kPa$) and towards the end of the transition boiling regime (with moderated pressure, $p=242 kPa$). These dissensions may be due to both experimental and numerical uncertainties; for example, some uncertainties could arise from the approximations made in the method of initialization of the numerical liquid film on the wall (see the precedent section). Nevertheless, the suggested correlations for T_N and T_L seem to behave correctly and the orders of magnitude and the tendencies observed experimentally are well respected.

Conclusions

Based on previous experiments from the literature, relationships representing the variation of the temperatures of Nukiyama and Leidenfrost with the gas pressure were suggested and validated using a liquid film boiling (LFB) model developed recently [7]. The numerical results of the new correlations and the LFB model compare fairly well with the experiments under various ambient gas pressures which are typical for several combustor devices like internal combustion engines.

Lastly, it is useful to recall that a particular attention must be carried to the determination of Nukiyama and Leidenfrost temperatures at atmospheric pressure. Also, other validation tests must be carried out in our future work in order to confirm the validity of the suggested correlations for multi-component fuels.

Nomenclature

| | |
|----------|---|
| A | atomic weight of surface material [kg] |
| C_p | specific heat at constant pressure [J K ⁻¹] |
| d | diameter [m] |
| h | liquid film thickness [m] |
| k | thermal conductivity [W L K ⁻¹] |
| p | pressure [Pa] |
| r | radius [m] |
| T | temperature [K] |
| V | volume [m ³] |
| δ | thickness of the vapor cushion |
| ϕ | contact angle [degrees] |
| ρ | density [kg·m ⁻³] |
| | vapour-liquid surface tension [N/m] |

Subscripts

| | |
|-----|--------------------|
| 0 | initial conditions |
| b | boiling |

| | |
|------------|-------------------------|
| <i>c</i> | critical |
| <i>cr</i> | Nukiyama or Leidenfrost |
| <i>f</i> | fluid |
| <i>L</i> | Leidenfrost |
| <i>max</i> | maximum |

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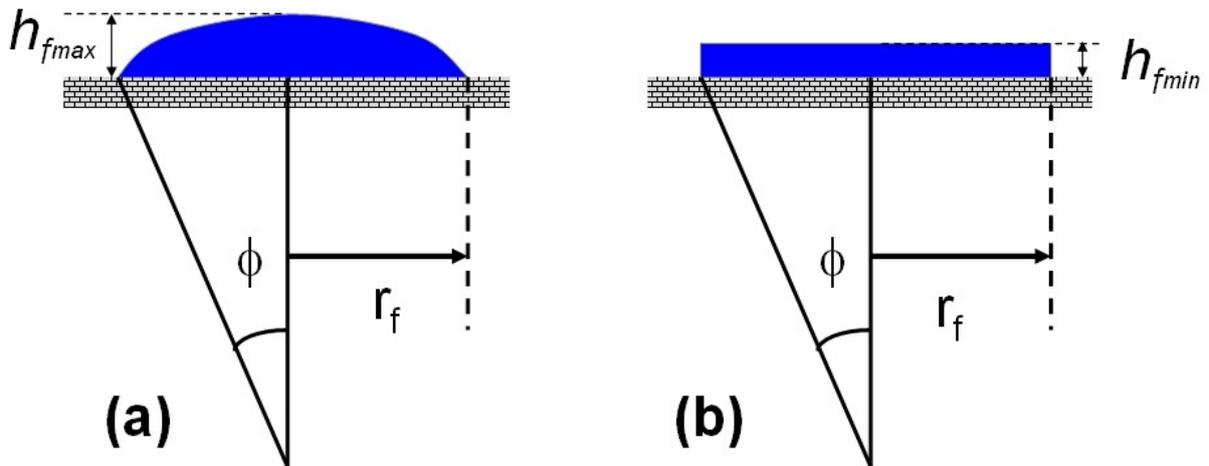


Figure 1. Numerical initialization of a droplet deposited on a wall. (a) Schematic and notations for Nagaoka model [25]. (b) Minimal film thickness, h_{fmin} definition

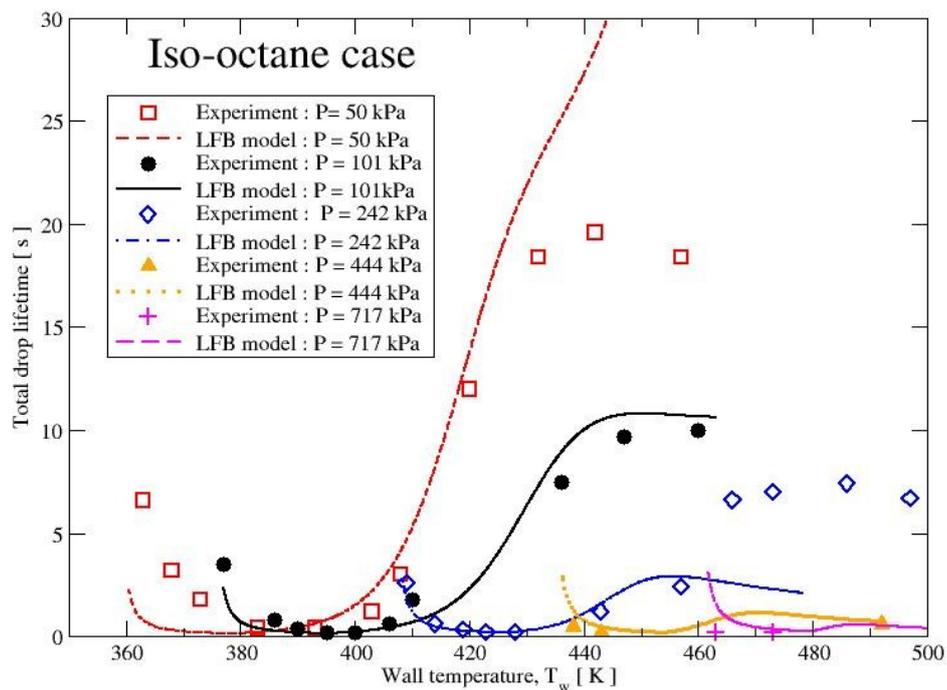


Figure 2. Influence of ambient gas pressure on the lifetime of an iso-octane droplet. Comparison of the LFB model results with the measurements of SRM [16]