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, 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. 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 [1] 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 Diesel engines, the fuel injection often occurs 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 [2]. 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. 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 objective of this paper is to present a new correlation for the calculation of the Leidenfrost and Nukiyama temperatures as function of the gas pressure. Finally, available experimental lifetime curves of droplets are used to validate the suggested new correlation for different ambient gas pressures [3].

Suggested Nukiyama and Leidenfrost temperatures correlations with gas pressure

Temple-Pediani [4] and more recently Stanglmaier et al. [3] have studied the effect of the ambient gas pressure on the evaporation of a droplet posed on a hot wall. 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 [5]. 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 differ-

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ences 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 [1] by the following expressions:

$$T_{cr} = T_{sat} + \Delta T \tag{1}$$

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

$$\Delta T = \begin{cases} T_{cr|1bar} - T_b & if\left(p \le 1 \text{ bar}\right) \\ \dfrac{\left(T_{cr|1bar} - T_b\right) - A}{T_c - T_b}\left(T_c - T_{sat}\right) + A & if\left(p > 1 \text{ bar}\right) \end{cases} \tag{2}$$

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 $A = Max\left(1, T_{cr|1bar} - T_c\right)$ 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=1 bar*) are supposed to be provided by lifetime curves of fuel droplets obtained experimentally in conditions close to those of the target application. In this paper, the values $T_N = 395K$ and T_L =463K which have been obtained by Stanglmaier et al. [3] at atmospheric pressure are used.

New correlations validation

The validation of the suggested correlations (1)-(2) is carried out mainly on the basis of experimental data resulting from the article of Stanglmaier et al. [3], referred to below as SRM. In these experiments, the lifetime durations of rather bulky droplets (d_0>2 *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.

Results and Discussion

The suggested correlations for T_N and T_L have been used in conjunction with the LFB model [1]. **Error! Reference source not found.** compares the numerical results with the experiments of SRM [3]. 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 [3, 4]. 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 [1]. 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.

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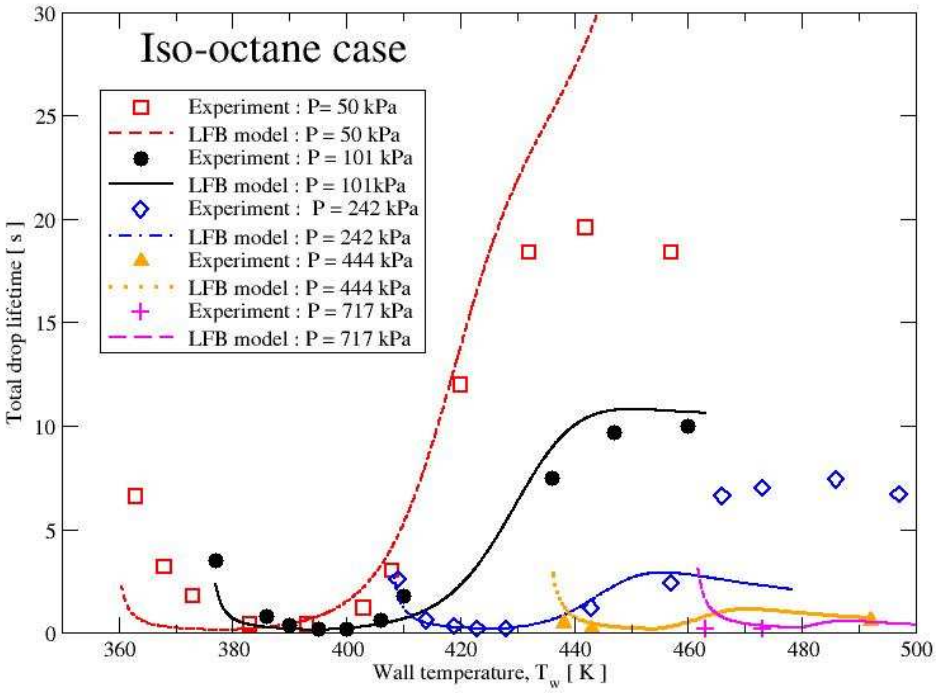

Figure 1. Influence of ambient gas pressure on the lifetime of an iso-octane droplet. Comparison of the LFB model results with the measurements of SRM [3].