A comprehensive experimental study on nucleate boiling in gasoline and gasoline-ethanol blends

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A B S T R A C T

Recent advances in fuel research have identified many benefits associated with heating fuels before they are injected into internal combustion engines, including improved cold starting and reduced greenhouse gas emissions. Extensive research has also been carried out into alternative, renewable biofuels. Of these, ethanol, which is normally used in ethanol-gasoline blends, is one of the most promising. However, although the characteristics and uses of heated fuel have been much discussed in the literature, it is important to improve our understanding of the fuel-heating process, which frequently involves nucleate boiling. This paper describes a comprehensive, novel experimental study of nucleate boiling in pure gasoline, ethanol and gasoline-ethanol blends. The heat transfer coefficient, critical heat flux and hysteresis effect are analyzed for each test fluid, and some considerations on the pressure effect are presented. For all the gasoline-ethanol blends, the heat transfer coefficient and critical heat flux increased with increasing pressure. Addition of ethanol to gasoline did not significantly change the heat transfer coefficient until the mole fraction exceeded 35%. The behavior of the heat transfer coefficient and critical heat flux indicates the existence of an azeotrope close to an ethanol mole fraction of 20%. Finally, gasoline exhibited partial nucleation during increasing heat flux at pressures greater than 202 kPa. Addition of ethanol to pure gasoline gradually eliminated this behavior until total nucleation was achieved.

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1. Introduction

Reduced emission of pollutants and more efficient energy use are two important trends in engine and transportation research, both of which have motivated many studies on topics such as combustion efficiency and potential alternative fuels. One of the most promising such fuels is ethanol, which has many advantages, including the fact that it is a renewable biofuel with a virtually unlimited supply, unlike petroleum.

Parametric effects and engine conditions have been extensively investigated to identify the most effective ways of using renewable biofuels. An example is the use of heated fuel and the benefits it offers in internal combustion engines. Sales and Sodré demonstrated that port-injection of ethanol at higher temperatures significantly reduces pollutant emissions (especially CO and unburned fuel) during cold start and engine warm-up compared with injection of gasoline at ambient temperature [1]. Huang and Hong reported a substantial reduction in CO and HC emissions in applications involving direct injection of heated ethanol [2].

Studies on other important topics such as fuel atomization, droplet evaporation and fuel phase equilibrium also consider the benefits of fuel heating and the use of gasoline-alcohol blends. In relation to fuel atomization, Fajgenbaum and Santos [3] and Nigra Júnior [4] showed that injection of heated fuel (gasoline and ethanol) results in more droplets with smaller diameters, improving combustion efficiency. Huang et al. [5] reported similar results but observed flash boiling, an undesirable phenomenon, when the fuel was heated up excessively, causing the injected fuel to lose its spray characteristics and decreasing its penetration.

Fuel droplet evaporation has also been widely studied to understand the mechanisms involved and better predict droplet behavior after injection into internal combustion engines [6–8]. When gasoline-ethanol blends are used, several issues related to the phase equilibrium characteristics must be taken into consideration [9], especially when water is present in the mixture [10]. Other studies have modeled the phase equilibria of gasoline-ethanol blends [11], including for flash boiling simulations [12].

The importance of studies on the use of heated fuel in internal combustion engines and the characteristics of gasoline-ethanol blends is reflected in the wealth of literature on these topics. Despite this abundance of studies, however, a better understanding

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of the fuel heating process is needed. Oliveira et al. [13] discuss the basic thermodynamics and heat transfer phenomena associated with fuel heating for cold starting of internal combustion engines. They note that nucleate boiling plays an important role in current fuel-heating systems because these usually involve dissipation of large amounts of power through small surfaces, resulting in high heat fluxes and, consequently, bubble formation. It is therefore essential when designing fuel heating systems to understand thoroughly the characteristics of boiling heat transfer in ethanol, gasoline and gasoline-ethanol blends as well as their limiting conditions, such as the critical heat flux (CHF).

Because it is one of the most efficient processes for cooling heated surfaces, nucleate boiling has been the subject of many heat-transfer studies. Boiling is well understood in ethanol [14–16] but has yet to be studied in detail in gasoline and gasoline-ethanol blends. Although Kusumowardhoyo and Subiakto [17] and Kusumowardhoyo and Hardianto [18] studied boiling in these fuels, their analysis is somewhat superficial and they provide very few details about their results and how their proposed correlation could be used.

This paper describes a comprehensive, novel experimental study on nucleate boiling in gasoline (PETROBRÁS S-50), anhydrous ethanol and gasoline-ethanol blends. The effects of pressure, fluid composition and hysteresis are investigated. The effect of the addition of ethanol to gasoline on nucleate boiling is also discussed and the question is asked whether ethanol is merely one more component among the hundreds of hydrocarbons in gasoline or it confers distinct boiling heat transfer characteristics on the blend because of its different properties.

The CHF at various pressures is evaluated for all the test fluids. Although CHF is highly dependent on the size of the surface [19,20] and the experimental results are therefore only valid for the test section used here (a platinum wire), the effect of the composition of the fluid on the CHF can be evaluated by comparing the results of the different experiments.

2. Theoretical overview

2.1. Nucleate boiling in mixtures

The boiling heat transfer phenomenon in gasoline and gasoline-ethanol blends can be analyzed using concepts related to mixture boiling, which can be found in the literature [19,21–27]. Because of the preferential evaporation of more volatile components, the fluid temperature near the heating wall increases (as reported by Sakashita [27]) and, consequently, the wall temperature increases as well. Therefore, mixtures have a lower heat transfer coefficient (*HTC*, given by Eq. (1)) than the ideal value (*HTC$_{id}$*, given by Eq. (2)), which is the inverse of the arithmetic mean convective thermal resistance weighted by the mole fraction of each component. However, at the azeotropic composition, the HTC of the mixture is the same as the ideal HTC because there is no preferential evaporation of the more volatile components. In Eqs. (1) and (2), q''_w is the heat flux, T_w the wall temperature, T_f the fluid saturation temperature (if the fluid is a pure component) or boiling point (if it is a mixture), x_i the mole fraction of the *i*th component, *HTC$_i$* the HTC of the *i*th component and N_{comp} the number of components in the mixture.

$$HTC = \frac{q''_w}{T_w - T_f}$$

(1)

$$\frac{1}{HTC_{id}} = \sum_{i=1}^{N_{comp}} \frac{x_i}{HTC_i}$$

(2)

The reduction in the HTC with mixtures has been investigated with a large variety of fluids, either with binary and ternary systems. Fujita and Tsutsui tested several binary mixtures with water, benzene and alcohols (methanol, ethanol, and *n*-butanol), and they observed the reduction in the HTC with mixtures, except at the azeotropic compositions [22]. Later, the same authors tested binary and ternary mixtures of R-134a, R-142b and R-123 and, again, they observed a degradation in the HTC with mixtures [24]. Vinayak Rao and Balakrishnan tested ternary systems of acetone/isopropanol/water and acetone/methylethylketone (MEK)/water and also observed that the HTC with mixture was always lower than with the pure components [23]. In more recent works, the same behavior was reported by Gong et al. after testing mixtures of ethane and isobutane [26] and by Sathyabhama and Ashok Babu with binary mixtures of ammonia and water [25].

Low heat transfer coefficients can be expected in gasoline, as it is a blend of hundreds of hydrocarbons with different volatilities. However, the effect of adding ethanol to gasoline on boiling heat transfer is unknown, especially as alkane-alcohol mixtures are azeotropic [28]. In gasoline-ethanol blends the HTC may:

- increase if addition of ethanol brings the mixture close to an azeotropic point (which occurs with an ethanol mole fraction of around 20%, corresponding to the maximum vapor pressure in gasoline-ethanol blends [11]);
- decrease if addition of ethanol substantially increases the effective temperature of the fluid close to the wall [29]; or
- stay the same if ethanol is just one more component among hundreds of others that does not cause any significant change in the HTC when added to gasoline.

2.2. Critical heat flux (CHF) in mixtures

The CHF is the peak heat flux when a vapor film forms, reducing heat transfer and causing a consequent abrupt rise in the temperature of the wire. The earlier evaporation of more volatile components affects the CHF in mixtures because it induces local subcooling near the heating wall, which increases the CHF just as subcooling causes the CHF to increase in single components [19,30]. As the induced subcooling does not take place at the azeotrope, a local minimum of the CHF is found at this composition. Similarly, the CHF reaches a maximum at a composition close to that of the mixture with the largest difference between the vapor-phase and liquid-phase compositions, when mass transfer is highly limited and induced subcooling plays a greater role. As mentioned before, the induced subcooling was recently observed by Sakashita [27], who reported the liquid temperature near the heating wall is significantly greater than the mixture bubble point (in a test with a mixture of 2-propanol and water).

Reddy and Lienhard observed this behavior in CHF with mixtures of ethanol and water [30], finding the maximum CHF at the composition where the maximum effective subcooling took place (about 20% ethanol mole fraction). Sakashita et al. found an increase of up to 1.7 times in the CHF with binary mixtures of 2-propanol and water [31]. Arik and Bar-Cohen also observed an increase in the CHF with mixtures of FC-72 and FC-40 when compared with the pure components [32].

Another explanation for the mixture effect on CHF is the direction of the Marangoni flows, which may result in a CHF greater than or less than an ideal value if the mixture is, respectively, positive or negative, as explained by Fujita and Bai [33]. They tested several binary mixtures using benzene, *n*-heptane, water and alcohols (methanol, ethanol, *n*-butanol and ethylene glycol) and developed a correlation in terms of the Marangoni number.