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Surface Temperature of Hydrocarbon Droplet in Evaporation

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Nomenclature

r_0 = initial droplet radius
T_{ℓ_0} = initial liquid temperature
T_∞ = ambient temperature
U_∞ = infinite air velocity

I. Introduction

THE surface temperature of a droplet in evaporation has been the subject of many numerical studies.[1,2] Experimental works use different techniques, as in infrared thermography.[3] This work follows a numerical model and measurements of evolution of the droplets radius in evaporation, already undertaken at the Laboratoire de Mécanique, Acoustique et Instrumentation (LMAI).[4,5] Temperature measurements presented in this study are used to validate this model. This last is based on the film concept and provides the time evolution of the radius and surface temperature of a pure liquid droplet or mixture of fuels in evaporation in natural or forced convection.

II. Numerical Model

Our model[4,5] is a generalization of the model proposed by Abramzon and Sirignano.[2] This model is based on the film theory, where mass and heat transfer between the droplet surface and the external gas are considered to take place inside a thin gaseous film surrounding the droplet. At any time, the thickness of the film depends on the average Nusselt and Sherwood numbers that qualify these transfers. Film thicknesses limit the integration areas of the mass and energy conservation equations in the gaseous phase. The heat transfer equation is solved to determine the temperature distribution inside the droplet. In the case of the mixture, in addition to this equation, one solves mass distribution equations to determine the spacial evolution of the mass fraction. Mass and thermal balance were verified constantly at the droplet surface. The external radius limiting the integration areas of the conservation equation in the gaseous phase has been defined in the literature and depends on the modified Nusselt and Sherwood numbers.[2] The correlations defining the average Nusselt and Sherwood numbers have been proposed by Bouaziz et al.[5] for a hydrocarbon or a mixture of hydrocarbons. In forced convection, the correlations have been proposed by Renksizbulut et al.[6]

III. Experimental Setup and Computer Image Processing

The experimental setup[4] (Fig. 1) was used to evaporate one pure or liquid mixture droplet at atmospheric pressure and to record video and thermal images of the droplet. The synchronization of thermal recordings and video images was time based simultaneously.

A. Thermal Wind Tunnel

The pure or liquid mixture droplet is hung at the center of the test section at the extremity of a glass capillary (diameter 0.2–0.3 mm) fixed on a permanent holder. In the case of liquid mixtures, those are prepared and sampled by a hypodermic syringe constantly shaken to maintain the mixture homogeneity. When the droplet leaves the injection needle, one considers that the droplet is constituted with an homogeneous product corresponding to the prepared mixture. The phenomenon can be observed optically on each side of the test section. The recording begins just before the droplet is suspended. This apparatus is provided with a mechanical damper situated at the entrance of the measurement test section that allows the establishment of a permanent velocity and temperature flow in the test section.

B. Infrared System and Thermal Image Processing

The infrared thermography system is composed of an infrared camera (Inframetrics Models 760, 3–12 μm) equipped with two lenses. A video camcorder completes the system. Recorded thermal sequences are processed after acquisition by a specialized software (ThermaGRAM) that determines the surface temperature evolution during vaporization. This software gives directly the time evolution of temperature with only knowledge of the emissivity value of the studied object.

C. Video System and Image Processing

Sequences of evaporation are also recorded by a video system (camcorder 8-mm charge-coupled device, 470,000 pixels) equipped for macrophotography. A processing computer (image acquisition board and software) digitalizes and compresses video sequences with a maximum speed equal to 25 images/s. The spatial definition of an image is 320 × 240 pixels. The droplet in evaporation is illuminated from the rear, which increases the contrast and facilitates the extraction of the droplet outlines. This operation is made by scanning and detecting the gray level of the pixels of each image line. The droplet is assumed to have symmetry of revolution from which the real volume of the droplet is deduced. The equivalent radius of a sphere of the same volume is then determined to initialize the numerical model and to obtain the radius regression related to the time.

IV. Results and Discussion

We present the experimental results of the evaporation of pure liquid droplets (water, decane, heptane, and hexane) and mixture droplets (heptane–decane) with different initial compositions. The droplet diameter varied between 1.1 and 1.55 mm. Temperature profiles obtained by infrared camera are compared to results of the numerical model developed by the LMAI, in which only liquid physical properties and ambient conditions occur. The semi-experimental protocol is the following.

Evaporation of a Water Droplet

The model is validated by an infrared measurement with a distilled water droplet, whose emissivity value (0.96) is known. The experiment took place in forced convection in a hot airflow. Figure 2 shows

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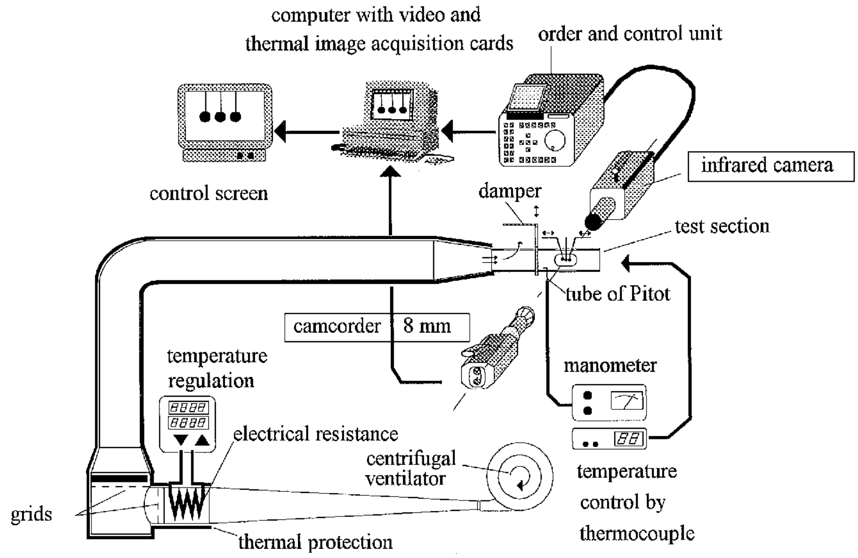

Fig. 1 Thermal wind-tunnel and measuring instruments.

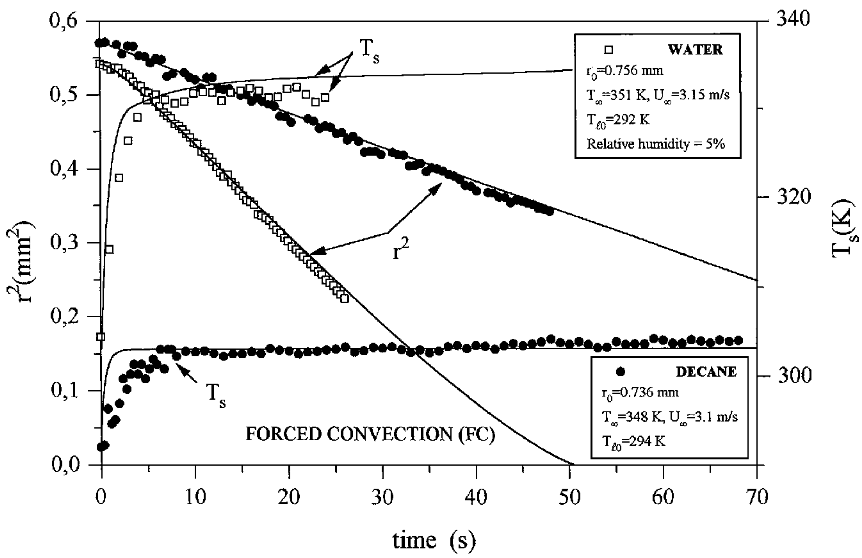

Fig. 2 Surface temperature and square radius of a water droplet and a decane droplet evaporated in a hot airflow.

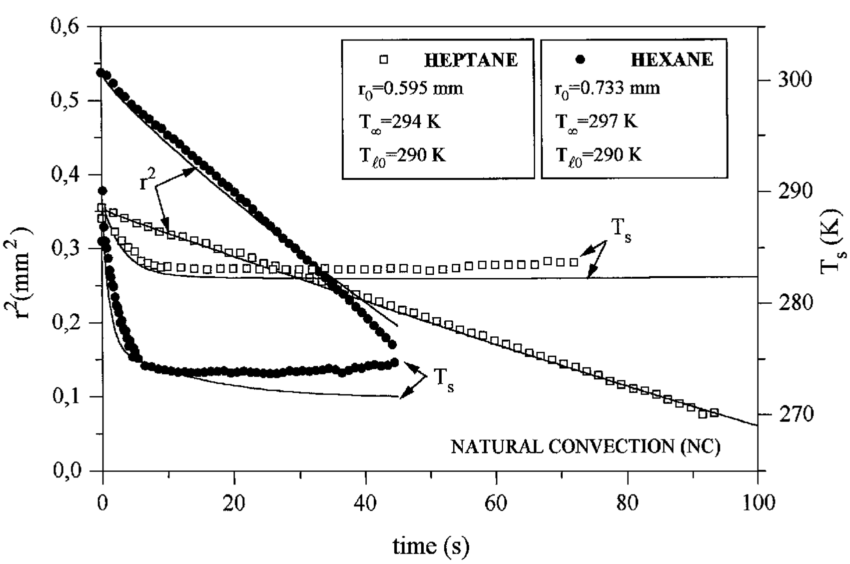

Fig. 3 Surface temperature and square radius of a heptane droplet and a hexane droplet evaporated in natural convection.

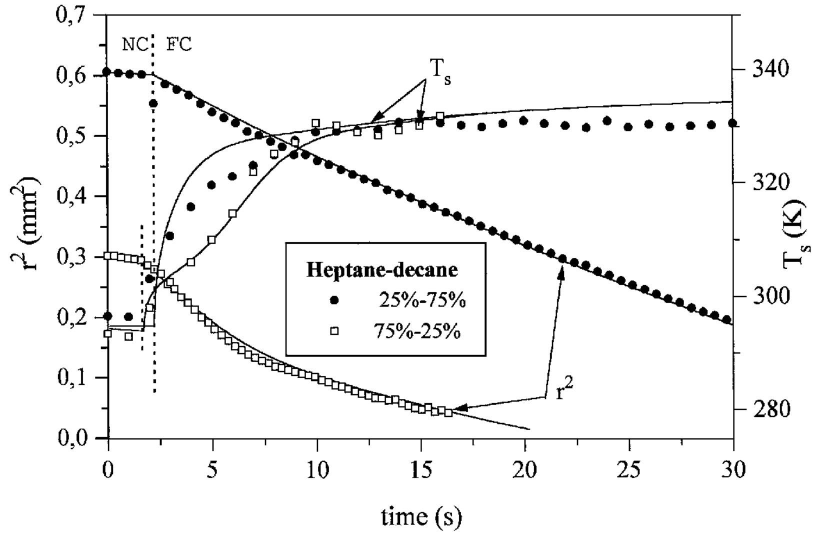

Fig. 4 Surface temperature and square radius of a mixture droplet evaporated in hot airflow.

results of this experiment. Considering that our numerical model is validated for the radius regression and for the surface temperature evolution in the water case, we are going to apply it to the case of a hydrocarbon (decane).

Emissivity and Evaporation of a Decane Droplet

According to the literature analysis, the emissivity of hydrocarbons in general is poorly known but assumed to be close to that of water and to range between 0.9 and 1. By considering a decane droplet evaporating in natural convection and using the ThermaGRAM software different emissivity values included in this range, we gradually obtained a value of 0.95 for which experimental results (Fig. 2) are in good agreement with the numerical model.

Generalization to Hydrocarbons

This 0.95 emissivity value is then generalized to the cases of every hydrocarbon (pure or in mixtures) studied. Inasmuch as the different hydrocarbons used have similar chemical composition, the emissivity values are also assumed to be very similar. The results of the evaporation of a heptane and hexane droplet in natural convection (Fig. 3) show globally good agreement between experimental and numerical results.

Evaporation of Mixture Hydrocarbon Droplet

The vaporization in forced convection of a liquid mixture droplet (heptane–decane) was also studied for two initial compositions (Fig. 4). We see, regardless of convection type studied, that numerical and experimental results are globally in good agreement, which confirms the validity of the universal emissivity value 0.95 used for all of the hydrocarbons studied.

V. Conclusion

This work presents a numerical and experimental study of the evolution of the surface temperature and the diameter of a pure or a liquid mixture droplet in evaporation. Vaporization took place in natural or forced convection. Experiments used an infrared camera to determine the surface temperature of the droplet and used a camcorder to follow simultaneously the droplet diameter evolution. The numerical model, based on the film concept, assumes that the droplet is surrounded by gaseous films in which mass transfer and thermal transfer take place. A preliminary study on the evaporation of a water droplet validates the results of the calculation model. A later study was conducted to determine the value of the hydrocarbon emissivity (decane). The obtained value (0.95) was used for all hydrocarbons and their mixtures. Experiments were carried out for pure products (decane, heptane, and hexane) and for one mixture (heptane–decane) with various initial compositions. We compared our data to the results obtained by the numerical model. This comparison gave satisfactory results.

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