XXI ICTAM, 15–21 August 2004, Warsaw, Poland

ON THE EVAPORATION OF A MONODISPERSE DROPLET STREAM AT HIGH-PRESSURE

Grazia Lamanna*, Han Sun*, Bernhard Weigand*, Davide Magatti**, Pietro Micciché**, Fabio Ferri**
*Institute of Aerospace Thermodynamics, Stuttgart University, D-70569 Stuttgart, Germany
**Department of Chemical, Physical, and Mathematical Sciences, University of Insubria, I-22100 Como, Italy

Summary A new experimental facility has been developed aimed at investigating the evaporation of free falling droplets at high pressure. A monodisperse droplet stream is generated in the upper part of the test rig and is embedded in a gas flow. The droplet speed is determined by means of a video technique and a stroboscope lamp. The droplet size is determined by means of the low- angle light scattering technique.

DROPLET EVAPORATION AT HIGH PRESSURE

Liquid droplet vaporization in a high-pressure, high-temperature environment is of relevance to combustion science and technology, due to the need of developing high-pressure combustion devices such as liquid-propellant rockets, gas turbines, and diesel engines. In all these systems, liquid fuels and/or oxidizer are usually injected into the combustion chamber as a spray of droplets, which undergoes a sequence of vaporization, ignition and combustion processes, at pressures levels well above the thermodynamic critical points of the liquids. Under these conditions, droplets initially injected at subcritical temperature may heat up and experience a thermodynamic state transition into the supercritical regime during their lifetimes. Consequently, for a proper design of the combustor and for an increased combustion efficiency, it is fundamental to model and predict correctly the process of transcritical vaporization. Its potential importance is so well recognized that numerous theoretical and experimental studies aimed at improving the basic understanding of the physics have been pursued [1, 2, 3, 4]. Unfortunately, albeit several evaporation models have been proposed in recent years, which include higher-order non-equilibrium effects and more complicated equation of states, their full validation has been hampered by the absence of reliable experimental data. Aim of our research activities is to develop a new test rig for studying droplet vaporization at high pressure/temperature through simplified and systematic experiments. Since the physics of fluid behaviour in the subcritical and supercritical regime is drastically different, due to the different length scales for heat and mass diffusion between the two regimes [5], we will focus at first on the subcritical regime. To that aim, we are currently developing an appropriate diagnostic tool for the determination of the evaporation rate of single-component droplets embedded in a gas flow.

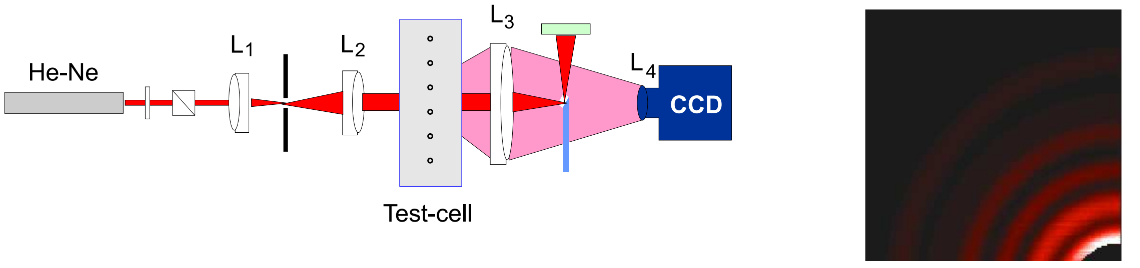
THE EXPERIMENTAL SETUP

High-pressure chamber

A new test rig has been built, where a monodisperse droplet stream evaporates under well defined conditions. The chamber can be pressurised till 80 bar and is thermally insulated to minimise heat losses. The cylindrical test section is $20\,cm$ long and has an internal diameter ϕ of $32\,mm$. The chamber is also equipped with a droplet generator, whose main components are a piezoelectric ceramic and an orifice plate. Upon exciting the piezoelectric element with a suitable frequency, a monodisperse chain of uniformly spaced droplets is obtained. A detailed description of the droplet generator can be found in [6]. The initial droplet temperature can be regulated by a heating/cooling device, and is controlled by a thermocouple. As test gas, nitrogen is used in order to exclude combustion processes. The droplets are falling vertically downwards on the centreline of the chamber and are embedded in a gas flow, in order to prevent condensation at the windows. The nitrogen flow is kept laminar and parallel to the droplet motion. The chamber is mounted on a x-y translator, so that the droplet size can be measured at different axial positions, through a set of two quartz windows $80\,mm$ long. The droplet velocity can be measured simultaneously by a CCD-camera combined with a stroboscope lamp and can be calculated from the known flash frequency of the stroboscope lamp and the distance between two consecutive droplets in the video recording.

Droplet sizing technique

The size history of the droplets is measured by means of the Low Angle Elastic Light Scattering (LAELS) technique, which was successfully applied by Ferri *et al.* [7, 8] to the characterization of large $[0.7 \div 80\,\mu m]$ polystyrene spheres. The method consists in measuring the light scattered by an ensemble of particles at various angles in the forward direction, as schematically illustrated in Fig. 1 (a). As light source, a He-Ne laser is used, whose power can be varied by means of a $\lambda/2$ retardation plate and a Glan-Thompson polarizer. The system of lenses L_1, L_2 creates a collimated beam ($\phi = 5\,mm$), which interacts with the droplet stream. The light scattered by the sample is collected by the lens L_3 and forwarded on the CCD camera. The lens L_4 conjugates the sensor plane with the focal plane of the lens L_3, therefore realizing a one-to-one mapping between scattering angles and pixel positions. A mirror, placed in the focal plane of lens L_3, deviates the transmitted beam upwards. The mirror is positioned in such a way that the focused transmitted beam hits its tip very close to the upper edge, allowing light scattered at very low angle to pass clear. This feature made it possible to use common CCD's as detectors, thus resulting in an increased angular resolution and sensitivity. An example of a typical diffraction pattern generated by a monodisperse droplet stream is shown in Fig. 1 (b).



(a) (b)

Figure 1. (a) Schematic representation of the experimental setup; (b) Typical diffraction pattern produced by a monodisperse droplet stream.

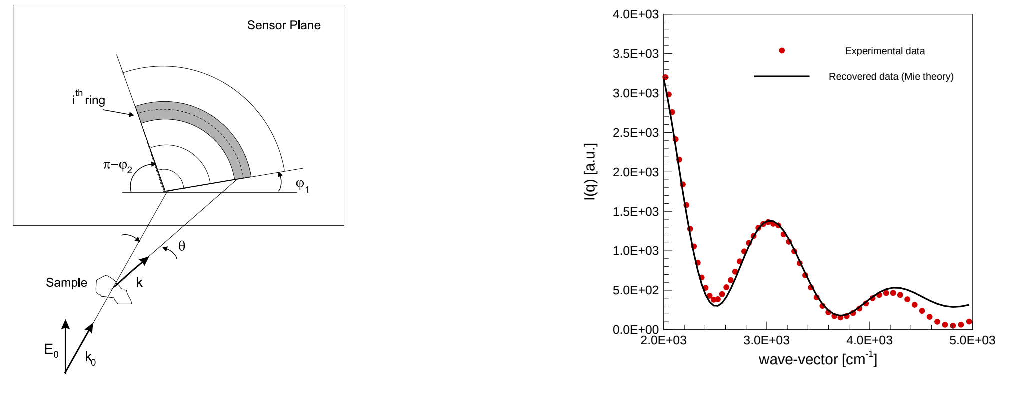
The distribution of light intensity is a function of two angles, the scattering angle θ and the polar angle φ, both defined in Fig. 2 (a). The dependence on θ carries information on the sample structure and size, while the dependence on φ accounts for polarization effects. As customarily done, it is possible to express the scattered intensity as function of the wave vector $\mathbf{q}$ only, defined as the difference between $\mathbf{k}$ (scattered wave vector) and k_0 (incident wave vector), i.e. $q = \mathbf{k} - \mathbf{k}_0$. The magnitude of $\mathbf{q}$ is related to the scattering angle by the relation

$$q = \frac{4\pi n}{\lambda} \sin\left(\frac{\theta}{2}\right), \tag{1}$$

where λ is wavelength of light in vacuum and n is the refractive index of the medium.
When the sample is a monodiperse ensemble of non-interacting droplets, the average scattered intensity is simply given by $I_{exp}(q) = n_d * I_d(q,r)$, where n_d is the number of droplets per cubic centimetre and $I_d(q,r)$ is the intensity scattered by a droplet of radius r:

$$I_d(q,r) = \frac{I_{exp}(q)}{n_d} = \frac{1}{\Omega} \int \mathcal{F}(\theta,\varphi,r)\, d\Omega, \tag{2}$$

averaged over the acceptance solid angle Ω that corresponds to q, $\mathcal{F}(\theta,\varphi,r)$ is the scattered intensity per unit solid angle provided by Mie theory, and the relation between the scattering angle θ and q is provided by Eq. (1). The images are processed by dividing the pixel matrix in concentric rings, centred on the optical axis, so that each ring corresponds to a specific wave-vector associated to the scattering angle θ. For the present experimental configuration, we used 80 concentric contiguous quarter of rings scaled according to a geometrical progression. Equation 2 is inverted by using a nonlinear iterative algorithm, developed by Ferri *et al.* [8]. As an example of the potential of the method, a preliminary result is shown in Fig. 2(b), where the experimental and reconstructed angular intensity distributions are plotted for the case of iso-propanol droplets with an average nominal diameter of 54 μm.



(a) (b)

Figure 2. (a) Schematic representation of a typical detector for LAELS measurements; (b) Comparison between experimental and reconstructed angular intensity distributions in the case of iso-propanol droplets with an average diameter of 54 μm.

References

[1] Sato J.: Studies on droplet evaporation and combustion in high pressure. AIAA 93-0813. *31st Aerospace Sciences Meeting*, 11-14 Jan, Reno, NV, 1993.

[2] Nomura H., Ujiie Y., Rath H.J., Sato J., Kono M.: Experimental study on high pressure droplet evaporation using microgravity conditions. *26th International Symposium on Combustion*, pp. 1267–1273, 1996.
[3] Harstad K., Bellan J.: An all-pressure fluid drop model applied to a binary mixture: heptane in nitrogen. *International Journal of Multiphase Flow* **26**: 1675–1706, 2000.
[4] Yang V., Lin N., Shuen J.-S.: Vaporization of liquid oxygen (LOX) droplets in supercritical hydrogen environments. *Combust. Sci. Technol.* **97**:247–270, 1994.
[5] Bellan J.: Supercritical (and subcritical) fluid behavior and modeling: drops, streams, shear and mixing layers, jets and sprays. *Progress in Energy and Combustion Science* **26**:329–366, 2000.
[6] Frohn A., Roth N.: Dynamics of Droplets. Springer Verlag, Berlin 2000.
[7] Ferri F.: Use of a charge coupled device camera for low-angle elastic light scattering. *Rev. Sci. Instrum.* **68**:2265–2274, 1997.
[8] Ferri F., Righini G., Paganini E.: Inversion of low-angle elastic light-scattering data with a new method devised by modification of the Chahine algorithm. *Applied Optics* **36**:7539–7550, 1997.