Coaxial atomization of a round liquid jet in a high speed gas stream: 
A phenomenological study

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Abstract Coaxial injectors have proven to be advantageous for the injection, atomization and mixing of propellants in cryogenic \( \text{H}_2/\text{O}_2 \) rocket engines. Thereby, a round liquid oxygen jet is atomized by a fast, coaxial gaseous hydrogen jet. This article summarizes phenomenological studies of coaxial spray generation under a broad variation of influencing parameters including injector design, inflow, and fluid conditions. The experimental investigations, performed using spark light photography and high speed cinematography in a shadow graph setup as main diagnostic means, illuminate the most important processes leading to atomization. These are identified as turbulence in the liquid jet, surface instability, surface wave growth and droplet detachment. Numerical simulations including free surface flow phenomena are a further diagnostic tool to elucidate some atomization particulars. The results of the study are of general importance in the field of liquid atomization.

1 Introduction

Cryogenic \( \text{H}_2/\text{O}_2 \) rocket engine thrusters use coaxial elements for injection where a liquid round oxidizer jet is atomized by a surrounding fast gaseous fuel stream. Typically, the liquid oxygen (\( \text{LO}_2 \)) leaves the injector in form of a turbulent free jet (\( \text{Re} \approx 10^7 \)) with a diameter of a few millimeters and an exit velocity of \( \text{U}_0 \approx 30 \) m/s. The atomizing hydrogen gas (\( \text{GH}_2 \)) enters the combustion chamber at similar Reynolds number as the liquid, but with an approximately 10-times higher velocity through an \( \approx 1 \) mm high, annular port. The combustion chamber pressure is of the order of 100 bar.

The prevalent atomization and flow phenomena, particularly the local distribution of the oxidizer droplets in the gaseous fuel environment as a result of injector design constitute the physical boundary condition for the subsequent combustion process and hence, significantly affect the ignition behaviour, reaction stability and heat load of the rocket engine.

One of the major aims of the experimental and theoretical studies is the formulation of theoretical injection and atomization models which, in connection with combustion or other engine system component models, ultimately support improvement of existing and development of future rocket engines. These efforts have to be seen in connection with the general trend to support, and possibly replace, costly experimental engine tests by numerical simulations. A further aim is to find out design criteria for coaxial injectors.

The studies presented in this article summarize the result of flow visualisation experiments under variation of influencing parameters including injector design, inflow- and fluid conditions. The investigations which deal with the problem of atomization are connected with complementary theoretical studies on propellant injection as e.g. turbulent droplet flow or atomization and spray modeling (Mayer et al., 1992; Mayer, 1993) based on experiences of previous investigations which were summarized in Krüüle et al. (1990, 1992), Faragó (1991), Faragó and Chigier (1992) and Buschulte (1989).

The physical complexity of coaxial atomization necessitates a cautious and well informed conceptual approach in approximating the real engine condition. Ignition experiments in a model combustion chamber using \( \text{LO}_2 \) and \( \text{GH}_2 \) indicate, that the atomization process is to a large extent independent of the high temperature effects found in real engines at least at chamber pressures up to 10 bar (Willems, 1993). Therefore, the atomization process is treated as a cold flow, purely fluid mechanical problem.

Experiments were performed operating single injector elements using water and air as easy to handle simulants. The research started with experiments under ambient conditions (Krüüle et al., 1990). However, from similarity considerations it can be derived, that increased representativity of experiments can be achieved with increased air density. Therefore, as a further step, experiments in a pressurized test chamber were performed with gas densities up to 25 kg/m\(^3\) at 20 bar chamber pressure.

2 Experimental setup

Only a brief description of the experimental system is presented. A detailed description of test facilities is given by Mayer (1993).

2.1 Injector setup

A single coaxial injector element (Model type I and 12) was operated under ambient conditions using water and air as simulation fluids supplied from a high pressure gas network and a pressurized water vessel, respectively (Fig. 1). The injector, constructed of stainless steel, has a straight inner tube to guide the liquid. The internal contours consist of an initial conical approach followed by a constant diameter section of around twenty diameters long. The tube is surrounded by a coaxial gap.
for the gas flow. The mass flow rates were calibrated measuring injection pressure differences.

The test chamber was designed for experiments at elevated gas pressures up to 20 bar (Fig. 2). The chamber essentially exists on a steel cylinder mounted on a buffer tank which keeps the test pressure and flow conditions constant. A single injector element (Model II) is mounted in the center of the upper chamber part. Lateral attached tubes, closed by optical windows, allow observation of the atomization process. Purge flow along the inner side of the steel cylinder and inside the window tube help to minimize contamination of optical windows by droplets mist.

3 Results

3.1 Experimental scope and conditions

The scope of flow conditions covered in this study, expressed by dimensionless numbers including the liquid Reynolds number \( \text{Re}_l \), the gas Reynolds number \( \text{Re}_g \), and the Weber number \( \text{We}_w \), is summarized in Table 1. The definition of the dimensionless numbers is as follows:

\[
\text{Re}_l = \frac{d_l \rho_l u_l}{\mu_l},
\]

Fig. 1. Model coaxial injector. Complete setup (top) and injector tip detail of model type I, IZ and II (bottom row), length in mm

Fig. 2. Test chamber with built-in injector (Type II) for experiments under elevated gas pressure conditions

2.2 Diagnostic means

Shadow photography and high speed cinematography proved to be powerful and complementary methods to observe the fast process of atomization (Hrbud, 1991). Single shots, which proved to be good for extensive parameter studies, were performed using a standard camera and a flash lamp (NANOLITE) in a shadowgraph setup. The 20 ns pulse duration of the light source was able to freeze the high speed flow phenomena.

High speed cinematography, i.e. the taking of high frequency image sequences, was used to resolve special time transient flow details. A drum camera (CORDIN, Dynafax 350) was operated together with a 1000 W film lamp in a shadowgraph setup, with which it was possible to obtain sequences of up to 80 successive images at a maximum repetition rate of 30,000 frames per second.