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Measurement of annular liquid film thickness in an open-end swirl injector

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ABSTRACT

An electrical conductance method was used to measure the liquid film thickness formed in an open-end swirl injector which is commonly used in Russian liquid-oxygen (LOX)/kerosene engines such as RD-120, RD-170, and RD-180. Two porous titanium electrodes and signal processing circuit based on lock-in amplifier were designed to measure the rapid variation liquid film thickness. The experimental results show that the liquid film thickness in the injector decreases with the increase of the pressure drop. The results of these measurements were compared with theoretical equations for predicting liquid film thickness in a swirl injector. An empirical equation to predict liquid film thickness in open-end swirl injector was modified based on the experimental results. Agreement between the modified equation and experimental results is demonstrated in this paper. This measurement method was also used to measure the liquid film thickness under pulsating conditions, and the study shows that our proposed method can be used to measure the liquid film thickness not only in the steady condition but also in the pulsating condition.

1. Introduction

The usage of open-end swirl injector is typical for modern LOX–kerosene rocket engines such as RD-120, RD-170 and its derivatives [6]. As shown in Fig. 1, the fuel injector and oxidizer injector are both open-end swirl injectors. This type of swirl injector needs to be studied because of the absence of convergent exit which is different from traditional swirl injector. Of all these studies on open-end swirl injector, the annular liquid film thickness formed in the swirl chamber is one of the crucial factors governing the film development and atomization processes. The liquid film is formed under the action of the centrifugal force of swirling liquid. In fact, liquid film thickness is one of the important input parameters for any swirl spray atomization models.

There have been many attempts to measure the annular liquid film thickness inside swirl injectors and then derive equations for estimation. As film thickness in the swirl injector are generally less than a few millimeters, accurate measurement is difficult, and this has led to the development of many measurement techniques. According to Clark [4], the film thickness measurement techniques are generally classified to four groups: film average methods, localized methods, point methods and spatial methods. Film average methods were applied in virtually all flow regimes such as annular or falling film flow to obtain an average film thickness value measured over a considerable length of film. There has been little recent study using film average methods due to their inability to provide information on local interface phenomena. The localized methods give a reasonably localized measurement (of the order of a few millimeters to a few centimeters) of the thickness of the film. The most commonly implemented film thickness measurement techniques, such as conductance and capacitance probes, belong to this group. This is probably due to their relative ease of use and general applicability to most flow systems. The third group of the film thickness measurement techniques is named point methods, which can obtain the continuous or statistical information at a point in a liquid film. But these methods are generally harder to implement and analyze than localized methods. Spatial methods consist of a number of point or localized measurement simultaneously in different areas of the film in order to build up a global picture of the film thickness structure for the area under study.

Of all these film thickness measurement techniques, the conductance method is probably most extensively used. The principle is that, because of the usually significant difference in specific conductivity between liquid and gas, a pair of probes will give a localized measurement of the conductance that will be a function of the thickness of the film between them. Basically, conductance is measured using a circuit containing a pre-determined electrode configuration and the reading is amplified and displayed by some output device. Film thickness can be determined from these conductance measurements if a calibrated relationship, preferably linear, can be established between the two parameters within the range of measurements. There are several conductance probe types in industrial applications: parallel-strip electrodes, arch electrodes,

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Nomenclature

a	Dimensionless coefficient, $a = 2(1-\varphi)^2/(2-\varphi)$	u	Axial velocity
C	Velocity of surface wave	v	Radial velocity
F	Sectional area of the annular liquid column	w	Tangential velocity
h	Liquid film thickness	z	Resistivity
L	Distance of the two cross-sections	ΔP	Pressure drop
m_l	Mass flow rate	μ	Coefficient of discharge, $\mu = \varphi\sqrt{\varphi}/\sqrt{2-\varphi}$
R_{in}	Swirl radius	μ_l	Dynamic viscous coefficient
R_w	Resistance of the annular liquid column	ξ	Amplitude of the liquid film
r_p	Radius of the swirl chamber	ρ_w	Density of the liquid
r_m	Radius of the air core	φ	Ratio of the area of liquid to the area of the discharge orifice
V_{in}	Velocity at the inlet		
V	Velocity of fluid		

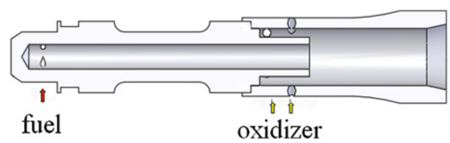

Fig. 1. Schematic of LOX–kerosene coaxial injector.

ring electrodes and concentric electrodes. Numerous studies on the conductance probe for liquid film thickness measurements have been reported.

Application of conductance ring electrodes in vertical pipes was reported by Kulov et al. [9] utilizing three ring electrodes for thickness measurements in downward two-phase flow in a 25 mm tube, and by Asali et al. [2] using a pair of annular metal electrodes in measurements of vertical upward annular flow in a 23 mm diameter tube. Andreussi et al. [1] and Tsochatzidis et al. [12] expanded the measurement theory of parallel strip electrodes to ring electrodes, and optimized the electrodes configuration. Tsochatzidis also investigated the effects of electrodes distance on the measurement results.

With respect to the study on the liquid film thickness in liquid swirl injector, Inamura et al. [7] measured the liquid film thickness at the swirl injector spout with a contact needle probe. Zhao and Gan [13] measured the fluctuation on the liquid film with a conductance needle. The disadvantage of needle method is that the needle could affect the flow in the injector. Rizk and Lefebvre [10] derived a general expression for film thickness which showed very satisfactory agreement over wide ranges of atomizer dimensions and liquid injection pressures, when compared with the experimental measurements. Then in 1986, Suyari and Lefebvre [11] measured the liquid film thickness using the electrical conductance between two electrodes located in the discharge orifice of a swirl injector. Bazarov [3] used two annular electrodes flush mounted in the injector wall to measure the liquid film thickness in swirl injector. Kim et al. [8] studied the effect of injector geometry on the liquid film thickness with conductance method similar to Suyari and Lefebvre. However, all the measurements are conducted in swirl injectors with convergent exit.

In this paper, a conductance method has been used to measure the dynamic annular liquid film thickness in an open-end swirl injector, which provides an initial condition for further analysis of breakup of the liquid sheet. A special measuring circuit is developed which can meet the requirements of steady and transient measurements of liquid film thickness. The measured liquid film thickness was compared to the results from empirical equations and a new equation was introduced based on this comparison.

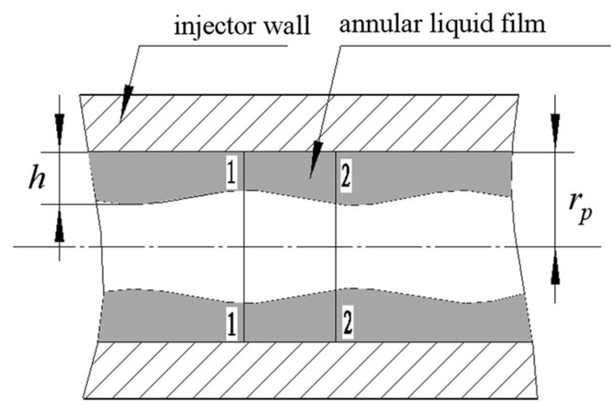

Fig. 2. Schematic of conductance method.

2. Measurement of liquid film thickness with conductance method

The theoretical analysis of using the conductance method to measure the liquid film thickness in a swirl injector was firstly conducted. Then the experimental equipments, measuring circuit and the error analysis for the measured liquid film thickness were performed.

2.1. Theoretical analysis of the conductance method

The flow is said to be irrotational if the vorticity is zero, in other words, $\nabla \times V = 0$. In cylindrical coordinates, for an axisymmetric flow, this has components x, r and θ, given by

$$[\nabla \times V]_x = \frac{1}{r}\frac{\partial(rw)}{\partial r} = 0 \tag{1}$$

$$[\nabla \times V]_r = -\frac{\partial w}{\partial x} = 0 \tag{2}$$

$$[\nabla \times V]_\theta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial r} = 0 \tag{3}$$

Integrating Eq. (1) gives rw =constant. This is a "free vortex". Eq. (2), r-term, indicates that the tangential velocity w does not change with the axial x-coordinate for any given value of the radial r-coordinate. As the radial velocity v is taken to be negligible, then the θ-component in Eq. (3) gives that the axial velocity component, u, is independent of r for any given x; in other words, it is constant across a cross-section in the swirl chamber. Hence, the annular liquid column between two cross-sections with an infinitesimal distance (compared to the surface wavelength) can be homogeneous.