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Effects of injector recess on heat flux in a combustion chamber with cooling channels

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ABSTRACT

An experimental study has been carried out to study the effects of recess length in swirl coaxial injectors on heat transfer in a combustion chamber with cooling channels. Liquid oxygen and kerosene (Jet A-1) were burned in a range of mixture ratios (2.12–3.07) and chamber pressures (57.3–82.3 bar) in small liquid rocket thrust chambers. Each thrust chamber had nineteen liquid–liquid swirl coaxial injectors. While changing the recess length of the injectors and operating conditions, temperatures of the cooling water passing through the cooling channels were collected and analyzed to calculate the heat flux in the combustion chamber. As expected, operating conditions such as oxidizer-to-fuel mixture ratio and chamber pressure had a large influence on the heat flux in the combustion chamber. The recess length of the injectors also significantly affected the heat flux in the combustion chamber, which showed that the longer recess length gradually increased the heat flux. It is thought that the variation of flame structure with respect to the recess length in swirl coaxial injectors was the main reason. Since heat flux is a very important factor in designing cooling channels, the effects of recess length on heat flux in a combustion chamber must be carefully considered.

1. Introduction

For the successful development of a liquid rocket engine thrust chamber, the designers should consider injection and atomization processes, combustion and ignition processes, nozzle design and optimization, chamber dynamics, heat transfer, and performance [31]. High combustion temperature and high heat transfer rate from the hot gases to the chamber wall make thrust chamber cooling a major design consideration. One or a combination of cooling methods among regenerative cooling, dump cooling, film cooling, transpiration cooling, ablative cooling, and radiation cooling are used in the combustion chamber, depending on propellants, chamber pressure, propellant-feed system, and chamber material [12,14]. In addition, a thermal barrier coating with low thermal conductivity can be applied on the surface of the chamber wall to reduce high heat transfer [8,20].

Kumakawa et al. [18] measured heat flux in two water-cooled calorimetric chambers using liquid oxygen (LOx)/gaseous hydrogen, LOx/gaseous methane, and LOx/RJ-1J as propellants and suggested empirical correlations. Similarly, many other researchers have performed analytical, experimental, and numerical studies on heat transfer correlations of supercritical hydrogen in regenerative cooling channels [23], heat transfer and coking characteristics of hydrocarbon fuels [22], cooling channel curvature effects and heat transfer [25,26], flow and heat transfer in a cooling channel with angled ribs [27], film cooling effects and heat transfer in a subscale combustion chamber [6,7]. They have tried to suggest improved models to predict accurately heat transfer in combustion chambers.

Among different types of injectors for liquid rocket engines, the swirl injector has been widely studied due to its favorable characteristics such as efficient mixing and uniform distribution of propellants [9,21]. A bi-swirl coaxial injector which consists of two swirl injectors with tangential holes in each swirl chamber is a special case of the swirl injector [4]. Swirl coaxial injectors which discharge LOx and kerosene have been successfully used in Russian rocket engines such as the RD-0110 and RD-107/108, and Korean development model engines [4].

A number of researchers have studied the bi-swirl coaxial injectors under cold-flow tests focusing on mixing, spray cone angle, film thickness, and drop size [16,29,30] and under hot-firing tests concentrating on discharge coefficient, combustion performance, and combustion stability [1–4,17]. Their results showed that the

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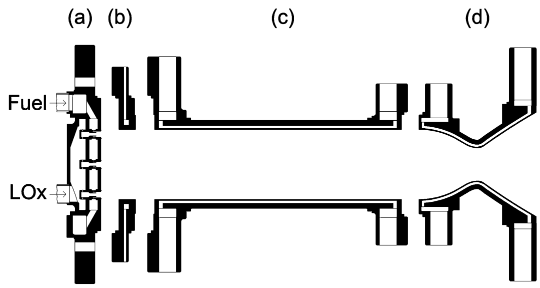

Fig. 1. Schematic of the multi-element combustor: (a) injector head, (b) film-cooling ring, (c) water-cooled cylindrical chamber and (d) water-cooled nozzle.

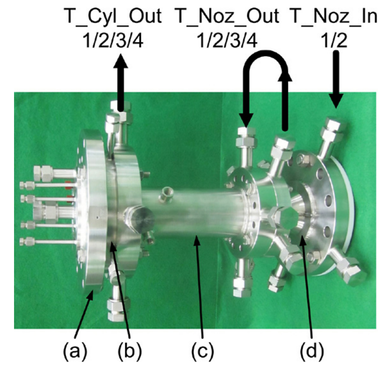

Fig. 2. Picture of the multi-element combustor and flow passage of cooling water: (a) injector head, (b) film-cooling ring, (c) water-cooled cylindrical chamber and (d) water-cooled nozzle.

Table 1
Injector dimension for each injector head.

Injector head	L_1 [mm]	*RN*
Head A	1.9	0.6
Head B	3.1	1.0
Head C	4.7	1.5

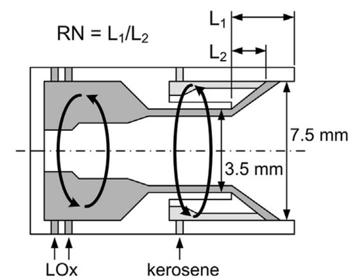

Fig. 3. Schematic of the liquid–liquid swirl coaxial injector and definition of the recess number.

recess length plays an important role in propellant mixing, combustion performance, and combustion stability. The recess length is the distance between the inner nozzle tip and the outer nozzle tip. The inner nozzle of the swirl coaxial injector is generally recessed from the outer nozzle tip [4]. The characteristic velocity, which indicates combustion performance in liquid rocket engines, generally increased with an increase of recess length in single-element combustors and multi-element combustors composed of LOx/kerosene swirl coaxial injectors [2,17].

Shear coaxial injectors, which generally feed gaseous hydrogen and LOx, have similar characteristics except that they do not have swirling flow. Using optically accessible single-element combustors equipped with a shear coaxial injector, a few researchers observed LOx/hydrogen and LOx/methane flames, and explained their flame structures [10,11,28]. Lux and Haidn [24] also have revealed in their investigation that a recessed LOx post considerably increases the flame expansion shortly after injection. Recessing the oxidizer tube has improved the characteristic velocity and stability margin [13].

The studies on swirl coaxial injectors and shear coaxial injectors showed that an increase in recess length significantly affected flame structure and combustion performance. However, the effect of recess length on heat transfer in a combustion chamber has not been reported yet in the open literature. Therefore, the objective of this study is to investigate the effects of the recess length in LOx–kerosene swirl coaxial injectors on heat transfer in the combustion chamber with cooling channels. The results of the study will provide a quantitative database for numerical simulation researchers. The recess length was changed from 1.9 mm to 4.7 mm in order to deal with external, intermediate, and internal mixing of LOx and kerosene spray sheets. Combustion tests were carried out over a wide range of chamber pressures and oxidizer-to-fuel mixture ratios to examine the effects of operating conditions on heat transfer in the combustion chamber.

2. Experimental methods

Fig. 1 shows the schematic diagram of the thrust chamber which consists of an injector head, a film cooling ring, a water-cooled cylindrical chamber, and a water-cooled nozzle. The present injector heads have nineteen identical swirl coaxial injectors, which are distributed uniformly along two concentric circles: one is located at the center, six on the first row and twelve on the second row. Each injector head is composed of injectors with different recess lengths as presented in Table 1. The cylindrical chamber has 120 straight-type channels 3 mm in height. The nozzle has 60 straight-type channels 3 mm in height until the expansion ratio of 4.5 and 120 straight-type channels 3 mm in height from the expansion ratio of 4.5 to the nozzle end. The internal diameter of the cylindrical chamber is 78.7 mm and that of the nozzle throat is 37.1 mm. The lengths of the cylindrical chamber and the nozzle are 280.0 and 133.1 mm, respectively. All the parts are bolted together and sealed with inserted copper gaskets.

As shown in Fig. 2, cooling water was supplied to the manifold in the rear flange of the nozzle, passed through the cooling channels, and emitted to the manifold in the front flange. The cooling water was again supplied to the manifold in the rear flange of the cylindrical chamber via four connecting tubes between the cylindrical chamber and the nozzle. Then the cooling water was passed through the cooling channels in the cylindrical chamber, collected in the manifold in the front flange of the chamber, and finally discharged into the atmosphere through four connecting tubes. K-type thermocouples were installed at the connecting tubes in order to measure the temperatures of the cooling water at the points of the nozzle inlet, the nozzle outlet (the cylindrical chamber inlet), and the cylindrical chamber outlet. More detailed information for the present thrust chamber can be found in [5].

Fig. 3 presents the schematic diagram of the present swirl coaxial injector. The injector configuration is similar to that of the previous research [2,4]. LOx in the oxidizer manifold enters into the swirl chamber through eight tangential holes, forms a swirl motion, and discharges through the inner oxidizer post into the combustion chamber. Kerosene (Jet A-1) in the fuel manifold is supplied via four tangential holes, swirls down, and passes through the outer fuel nozzle to come into the combustion chamber. A total of three different types of injectors have the same geometric dimensions except for the recess length between the inner oxidizer post tip and the outer fuel nozzle tip. The inner diameters of the oxidizer post and the fuel nozzle are 3.5 mm and 7.5 mm, respectively. The recess number (*RN*) is defined as a dimensionless parameter, which divides the recess length (L_1) by the distance be-