

Disintegration Process and Performance of a Coaxial Porous Injector postprint

Authors: Lee, K., Kim, D., Koo, J.

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Abstract

A flow control system that combined steady Vortex Generator Jets and Deflected Trailing-edge (VGJs-DT) to decrease the low pressure turbine (LPT) blade numbers was presented. The effects of VGJs-DT on energy loss and flow of low solidity low pressure turbine (LSLPT) cascades were studied. VGJs-DT was found to decrease the energy loss of LSLPT cascade and increase the flow turning angle. VGJs-DT decreased the solidity by 12.5% without a significant increase in energy loss. VGJs-DT was more effective than steady VGJs. VGJs-DT decreased the energy loss and increased the flow angle of the LSLPT cascade with steady VGJs. VGJs-DT can use 50% less mass flow than steady VGJs to inhibit the flow separation in the LSLPT cascade. The deflected trailing edge enhanced the ability of steady VGJs to resist flow separation. Overall, VGJs-DT can be used to control flow separation in LPT cascade and reduce the blade numbers of low pressure turbine stage.

Full Text

Preamble

Disintegration Process and Performance of a Coaxial Porous Injector

Keonwoong Lee¹, Dohun Kim¹, Jaye Koo²

¹Graduate School, Korea Aerospace University, Goyang, Republic of Korea

²School of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang, Republic of Korea

To understand the breakup performance of coaxial porous injectors, sprays from coaxial porous injectors with two different porous material cylinder lengths were compared with those from conventional shear coaxial injectors. For direct comparison, the wall injection lengths were designed to be equivalent to the recess depth value. Cold flow sprays were visualized using back-lit photography and

analyzed quantitatively with a laser diffraction apparatus to investigate the effects of momentum flux ratio and Weber number on breakup for each injector type. In the shear coaxial injector, a large liquid core was observed under low air mass flow rate conditions. However, destabilization of the liquid jet from the coaxial porous injector was almost complete within the inner region near the injector face plate. Additionally, better breakup performance under low gas flow rate conditions was obtained when the porous cylinder length decreased, while shear coaxial injectors showed better breakup efficiency when the recess length increased. In conclusion, the different breakup process caused by radial momentum in the inner region of the porous injector disintegrated the liquid core.

Keywords: Coaxial porous injector, Sauter mean diameter, Droplet size distribution

Introduction

Shear coaxial injectors and coaxial swirl injectors are widely used in spray and combustion devices. In a shear coaxial injector, the dominant factor in the atomization process is the shear force between high-velocity gas and low-velocity liquid. The shear injector offers several advantages for liquid rocket engine applications, including design simplicity, ease of close-set placement, and uniformity of the combustible mixture. However, weaknesses of the shear coaxial injector should be noted, such as low manufacturing tolerance for its simple design [1]. The swirl coaxial injector is widely used in Russian liquid rocket engines that employ kerosene fuel [2]. The primary characteristic of the swirl coaxial injector is that liquid propellants are injected as a hollow, cone-shaped sheet spray, which is easily disintegrated and mixed with a gaseous propellant jet or other liquid propellant swirl sprays. Several Asian, U.S., and European researchers have reported on the spray and combustion characteristics of coaxial swirl injectors for hydrocarbon-fueled liquid rocket engines. For example, Salgues et al. [3] compared the combustion efficiency and flame structure of swirl coaxial injectors with those of shear coaxial injectors. The swirl coaxial injector exhibited better characteristic velocity efficiency, defined as the ratio between the theoretical characteristic velocity from the NASA Chemical Equilibrium with Application (CEA) code and the actual characteristic velocity. They deduced that fast atomization and mixing of the swirl coaxial injector spray caused this improved combustion efficiency. However, swirl coaxial injectors also have disadvantages regarding design complexity [1].

Unlike swirl coaxial injectors, the coaxial porous injector was developed to improve the mixing characteristics of traditional shear coaxial injectors. Compared to the shear coaxial injector, which discharges gas and liquid jets axially, the gaseous jet of a coaxial porous injector is wall-injected radially through cylindrical porous material that encloses the axial liquid jet in the recess region. This design aims to enhance liquid-gas spray mixing by increasing the momentum transfer efficiency from the high-speed gas jet to the liquid jet.

Previous studies experimentally examined the feasibility of using a coaxial porous injector as a combustion device. The coaxial porous injector demonstrated higher combustion efficiency than the coaxial shear injector in a subscale liquid rocket combustor [4]. The structure of the reacting spray from a coaxial porous injector was observed using shadowgraph techniques [5]. From density gradient magnitude analysis of shadowgraph images, researchers surmised that improved combustion efficiency resulted from increased evaporation rate at the interface between the center liquid jet and peripheral gaseous jet. However, the efficiency-improvement mechanism of the coaxial porous injector was not clearly understood throughout previous studies. Generally, shear coaxial injectors with recess length exhibit better atomization performance than those without recess length, but in coaxial porous injectors, if the wall injection length increases, the injection velocity naturally decreases, meaning the momentum flux of the gaseous propellant also decreases.

In the present study, the non-reactive spray of the coaxial porous injector was visualized and breakup mechanisms were compared with those of the shear coaxial injector under nearly equal injection conditions using a precision flow control system and laser diffraction apparatus.

Nomenclature

Symbols

A area (mm^2)
d diameter (mm)
J momentum flux ratio
L length (mm)
 \dot{m} mass flow rate (g/s)
Re Reynolds number
SMD Sauter mean diameter (m)
t thickness (mm)
V velocity (m/s)
We Weber number

Greek Letters

viscosity
density
surface tension

Subscripts

a annular gap
g gaseous simulant
l liquid simulant
r recess
sci shear coaxial injector
pci porous cylinder injector

Experimental Apparatus and Conditions

Experimental Apparatus and Methods

The geometries of the shear coaxial injector and coaxial porous injector are shown in Fig. 1 [Figure 1: see original paper]. Liquid jets are injected axially through the center bore of both injectors. In the shear coaxial injector, the gaseous propellant develops into an axial flow at the annular gap, so gas and liquid jets flow horizontally. The momentum of the gaseous jet is then transferred through shear interaction induced by the velocity gradient. In the coaxial porous injector, the gaseous propellant is wall-injected radially through the cylindrical porous surface, constructed from sintered stainless steel with a 90 μm mean metal particle diameter. The radial gas jet then develops into an axial flow within the recess region. Creating this difference in gas injection direction between the two injectors aims to improve momentum transfer from the gaseous jet to the liquid jet. In this paper, the simplified notations for the shear coaxial injector and coaxial porous injector are referred to as SI and PI, respectively.

The geometrical dimensions and injector names in this study are listed in Table 1. In a coaxial porous injector, the recess depth is the distance between the center liquid post end and the injector face plate. The wall injection length of the PI corresponds to the recess depth of the SI. The center liquid post diameter is 1.5 mm and the gas outlet diameter, equal to the inner diameter of the PI, is 4.5 mm. The thickness of the porous cylinder is 1.5 mm. Two SI configurations with different recess lengths (SI-1 and SI-2) and two PI configurations with different wall-injection lengths (PI-1 and PI-2) were compared. As described above, the wall-injection length of PI-2 equals the recessed length of SI-2, which is used to observe the effect of radial gas injection through the PI. The PI-1 injector has a shorter wall-injection length but the same injector tip area, a configuration used for investigating the effect of radial momentum magnitude on the liquid breakup mechanism.

To characterize spray flow conditions, three familiar non-dimensional numbers were employed. The first is the momentum flux ratio, J , defined as the ratio of annular gas flow momentum to liquid jet momentum as shown in Eq. (1). The velocities of liquid and gas simulants were determined using the basic mass flow rate equation, as shown in Eqs. (2) and (3).

Air is provided by an air compressor and water is transferred from a cistern to the injector via a piston pump. The liquid mass flow rate is controlled by a metering valve and bypass tube line. Back-lit photography visualizes liquid breakup behavior. A stroboscope with a planar-convex lens provides illumination, while spray patterns are captured with a Nikon D700 DSLR camera and macro lens. Additionally, the laser diffraction apparatus manufactured by Sympatec (Helos/Vario-KF) [6] uses a 5 mW, 633 nm He-Ne laser with a 29 mm beam diameter. The measuring section was located 15 times the liquid center post diameter from the injector face plate.

Experimental Conditions

Several researchers reported that mixing characteristics of single- or two-phase coaxial flow are affected by the momentum flux ratio obtained from numerical or experimental studies [7-10]. For the cold flow experiment, the momentum flux ratio was calculated using propellant densities observed under ambient conditions. Eq. (4) gives the liquid jet Reynolds number, the second dimensionless parameter used in this paper. The third flow-condition parameter is the aerodynamic Weber number, the ratio between inertia and surface tension, given by equation (5), where a lower Weber number indicates a larger surface tension effect on liquid jet instability.

The experimental conditions are shown in Table 2, and the diagram originally authored by Chigier and Reitz is reproduced [11] in Fig. 2 [Figure 2: see original paper]. The experimental conditions are also plotted. In Fig. 2, case 1 lies in the membrane-type breakup region, while the others fall in the fiber-type breakup region.

Numerical Method and Conditions

To obtain the velocity distribution of gaseous propellant, numerical calculations were performed using commercial software. The second-order upwind scheme and realizable k-epsilon model were applied. The 2D axisymmetric domain and boundary conditions are shown in Fig. 3 [Figure 3: see original paper]. The pressure outlet boundary was assumed to be atmospheric pressure.

Results and Discussion

The effects of momentum flux ratio on macroscopic spray pattern and breakup regime were observed for each injector configuration, with the liquid jet Reynolds number (Re_{liq}) fixed at approximately 2000 for these experiments, indicating laminar flow conditions. The backlit visualization images in Fig. 4 [Figure 4: see original paper] show macroscopic spray patterns for the four injector configurations. The water/air spray of the shear injectors exhibited general disintegration behavior according to spray condition changes [8, 12]. The spray patterns in each column were captured under nearly equal flow conditions. As shown in Fig. 4, breakup lengths decreased with increasing air mass flow rate. Furthermore, liquid droplet diameters of PI appeared smaller than those of SI.

For the lowest air mass flow rate (Case 1), sprays from both SI configurations demonstrated typical membrane breakup. In contrast, the most significant differences in PI sprays were the disappearance of the liquid core and the level of oscillation. This occurred because the momentum of the gaseous jet from PI transferred to the liquid jet more efficiently than the momentum from the gaseous jet of SI in the recessed region. The liquid was almost completely disrupted within the recessed region, with only liquid droplets emerging from the injector tip.

As air mass flow rate increased to 1.2 g/s (Case 2), the liquid core from SI showed severe oscillatory motion and large liquid lumps were observed. Additionally, membrane structure formation was reduced, exhibiting fiber-type breakup mode as shown in the Fig. 2 regime. In contrast, liquid cores from both PI configurations had already disintegrated within the inner injector region, with only tiny lumps and droplets observed. Furthermore, liquid droplets of PI-1 appeared much smaller than those of PI-2.

As air mass flow rate further increased to 1.6 and 2.0 g/s (Cases 3 and 4, respectively), the liquid core and large lumps from SI still remained within the near-injector region, and typical super-pulsating disintegration [11] was observed. Super-pulsating disintegration generally occurs when Re_{liq}/W_{egas} is smaller than 100 in coaxial flow, but due to the recessed liquid injection post, super-pulsating disintegration occurred even though this criterion was not satisfied. Additionally, for both cases, droplet dispersion angle narrowed owing to entrainment of the high-speed annular gas jet. However, liquid cores of PI-1 and PI-2 injectors appeared to vanish for cases 3 and 4, suggesting that PI had higher liquid-atomizing capability and much smaller droplet diameter than SI.

The SMD values for each case are shown in Fig. 5 [Figure 5: see original paper], and relative SMD values are shown in Fig. 6 [Figure 6: see original paper]. Relative SMD is defined as the SMD value normalized by that of SI-1. Under all experimental conditions, SI-1 and SI-2 showed similar SMD distributions, while both PI SMD values were lower than those for SI. PI-1 particularly exhibited low SMD values. The difference between SMD values decreased with increasing Weber number.

Droplet size distributions for each case are shown in Fig. 7 [Figure 7: see original paper]. As air mass flow rate increased, growth in the smaller droplet size peak was observed alongside decline in the larger droplet size peak. This phenomenon caused bimodal droplet size distributions for the coaxial porous injector. Bimodal droplet size distributions are known to occur occasionally in effervescent atomizers [13]. Compared to distributions for the shear coaxial injector, there was a higher proportion of smaller droplets and lower proportion of larger droplets. This tendency was magnified for PI-2.

Velocity magnitude contours for PI-1 and SI-1 in Case 4 are shown in Fig. 8 [Figure 8: see original paper]. Additionally, gas velocity profiles for these cases at distances of 5 mm and 15 mm from the injector face plate are shown in Fig. 9 [Figure 9: see original paper]. In the SI-1 velocity magnitude distribution, the gaseous propellant flow headed toward the center region after passing the injector face plate. In contrast, since the gaseous propellant flow of PI-1 was injected radially, gaseous propellant accumulated in the inner region of the injector (the space between the liquid post tip and injector face plate) before spraying into the ambient environment. This difference is clearly observed in Fig. 9. Because of this difference, it is surmised that the liquid jet from PI is more disrupted than that from SI in the injector inner region under the same flow conditions.

These results indicate that while liquid jet atomization in shear coaxial injectors occurs from primary breakup of the liquid jet surface to secondary breakup of large droplets, atomization performance in coaxial porous injectors is superior because liquid jet disruption is almost complete within the injector inner region due to radial momentum of the gas propellant. Since the disruption process of the liquid jet is significantly faster than in shear coaxial injectors, secondary breakup also begins earlier. Through secondary breakup, smaller droplets are generated, so bimodal droplet size distribution is clearly observed in Fig. 7. This difference is illustrated in Fig. 10 [Figure 10: see original paper].

Conclusions

The non-reacting sprays of two SI and PI configurations with different geometries were observed using backlit visualization techniques and a laser diffraction apparatus. The cold-flow spray experiment revealed differences between breakup mechanisms of SI and PI using both photographic imagery and laser diffraction analysis. Additionally, the effect of wall-injection length on PI breakup behavior was observed.

In visualization images, only sprays from SI exhibited typical breakup modes such as membrane type, fiber type, and super-pulsating submode. Liquid cores and lumps remained even under higher gas mass flow rate conditions due to entrainment of high-speed gaseous propellant. In contrast, PI sprays showed disappearance of the liquid core under all experimental conditions, with dense liquid lumps rarely observed.

SMD values and droplet size distributions were also obtained. First, SMD values of the coaxial porous injector were lower than those of the shear coaxial injector under all experimental conditions. Between the coaxial porous injectors, PI-1 showed better SMD performance than PI-2, though this difference decreased under high air mass flow rate conditions. Additionally, bimodal distribution was observed for the coaxial porous injector. As air mass flow rate increased, the smaller droplet size peak increased significantly.

From experimental results, significant breakup performance differences existed between SI and PI. Although some SMD difference between PI-1 and PI-2 occurred under low air mass flow rate conditions, this difference decreased as air mass flow rate increased. It is widely known that short wall-injection length requires high supply pressure. Therefore, future studies examining the relationship between porous material and pressure difference in combustion environments to obtain optimal porous wall-injection area will be required.

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