EXPERIMENTAL INVESTIGATION OF THE PARAMETERS OF ADDITIVELY MANUFACTURED COAXIAL SWIRL INJECTORS

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INTRODUCTION

Modern development of the intense competition on the market of Liquid Propellant Rocket Engines (LPRE) is mostly driven by occurrence of many private space companies, crowdfunding space projects, etc., which inevitably leads engineers to seeking of rational solutions with the aim of decreasing production costs along with increasing of the efficiency of the parts. Usually for successful development of the rocket engine costly equipment as well as advanced manufacturing experience is in need which explains high overall manufacturing cost.

It is due to specific requirements for individual parts that application of conventional manufacturing of LPRE is typically associated with significant time expenses, decreasing the efficiency of the production cycle. When there is a lack of necessary equipment, funds, and time, it is of high priority to find new methods of LPRE components manufacturing which do not require special tools and numerous complex technological processes, etc. Thus, it is becoming widespread to use additive manufacturing which can significantly reduce the production cycle as well as decrease production expenses [1, 2, 3].

One of the most significant components of a LPRE is a Combustion Chamber (CC) which is at the forefront of development, especially in the case of newly designed engines. In some cases, designing and production of the chamber might compose up to ~50% of the overall engine cost, and its conventional design usually is associated with significant technological difficulties [1, 2]. Thuswise, it is of high priority to use additional

manufacturing for further design adaptation along with synthesis of the design solutions with unique properties [4–6].

In this work the application of additive manufacturing method for co-axial bipropellant swirl injectors production is considered. 30 coaxial bi-propellant swirlers of the internal mixing were manufactured using L-PBF technology. Numerous hydraulic tests of the injectors were performed with the aim of determining its characteristics. The aim was to observe individual operation of each injector as well as collaborated work of the coaxial injectors. Spay cone angle for both individual and collaborative operation mode was of a particular interest. The obtained data is analyzed and compared to the calculated values.

TASKS AND OBJECTIVES

The main objectives:

– Adaptation of the design of coaxial bipropellant swirl injectors to additive manufacturing.

– Use of refractory alloy.

– Use of easily accessible material.

– Determination of coaxial bipropellant swirl injectors characteristics by carrying out hydraulic tests.

– Comparing experimental with theoretical data.

MATERIALS AND METHODS

The considered coaxial bipropellant swirl injectors were manufactured using relatively easily accessible material Haynes 230. The alloy is capable of withstanding high (~1149°C) and low, cryogenic temperatures, maintaining outstanding oxidation resistance, decreased thermal-expansion co-efficient and great welding characteristics. As injectors are a part of a larger complex component, a mixing head which perceives a significant amount of heat flux during the engine operation, application of Haynes 230 is a rational decision.

Laser Powder Bed Fusion (L-PBF) [1, 2, 3] was chosen to be a manu-factured method. Consequently, a laser beam is used to supply energy for metal powder fusion during the building process (see Figure 1).

– Let us consider a simplified procedure of the manufacturing process (see Figure 2):

– Thinking of the main design concepts and ideas.

– Developing a 3D model using Computer Aided Design (CAD) sys-tem considering technological limitations of the printer (maximum unsup-ported printing angle of the surface, minimal printing diameter of holes

and slots, minimal wall thickness, etc.).

– Pre-printing model processing: conversion to .stl format, choice of the type and installation places of the supporting structures, etc.

– Printing process.
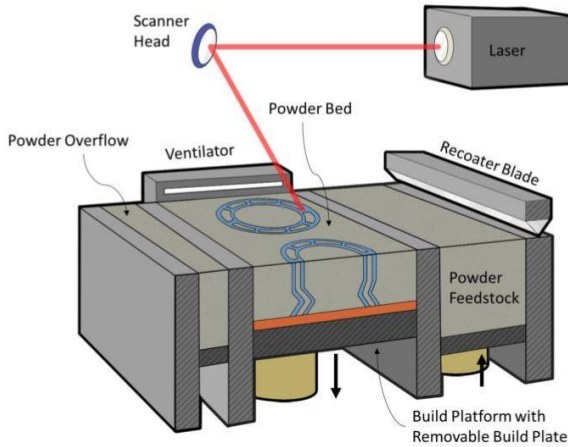
– Post-printing process.

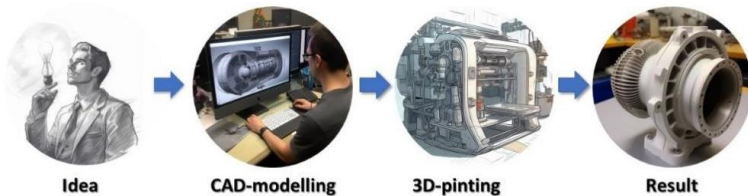Figure 1 – Laser Powder Bed Fusion process [1]

Figure 2 – Simplified procedure of the additive manufacturing process

It should be noted that currently there is no standard that regulates additive manufacturing cycle, in particular uniform quality control for produced parts. In that respect, 3D-printing parameters and post-printing procedures are often considered to be corporate property and are not subject to disclosure [2].

The objective of the hydraulic tests was to determine main characteristics of the coaxial bipropellant swirl injectors (pressure drop, spray cone angle). Each of the injectors consists of two parts: inner and outer swirl injectors (injector 1 and injector 2 respectively). The testing was performed for two regimes: individual operation of each injector and

cooperative operation of both injectors. Water was chosen as a working fluid. 30 specimens were divided into 6 groups with variation of the geometrical parameters (5 specimens per group). All geometrical parameters of the injectors were normalized to nozzle diameter **d (d2)** of the outer injector and are represented in Table 2.

Table 1 – Geometric characteristics of manufactured injectors

Parameter	Injector 1	Injector 2	
R	1.6	2.4	
d	0.44	1	
d_{in}	0.28…0.35	0.25…0.33	
n, pcs	3	1…2	
A	3.9…5.9	38.3…60.4	

A is a geometric characteristic coefficient of the injector:

$$A = \frac{R \cdot \frac{d}{2}}{n \cdot \left(\frac{d_{in}}{2}\right)^2}$$

where *n, pcs* is a number of tangential holes; *d* is a normalized nozzle discharge diameter (d1, d2); d_{in} is a normalized tangential hole diameter, *R* is a normalized swirl diameter.

RESULTS

According to experimental data, it is shown that between-specimen repeatability of pressure drops lies within the 5% range and is fully acceptable for engineering purposes (see Table 2). Discharge coefficient is determined following the equation:

$$\mu = \frac{\dot{m}}{f_c \cdot \sqrt{2 \cdot \rho \cdot \Delta p}}$$

where $\dot{m}$, kg/s – mass flow rate of the working fluid through the injector; $f_c = \frac{\pi \cdot d^2}{4}$, m^2 discharge nozzle cross-section; ρ, kg/m^3 – density of a working fluid; Δp, *Pa* – injector pressure drop.

Table 2

Injector 1						
Parameter	1	2	3	4	5	6
Re	8851	8851	8851	8851	7113	8851
Δp, kgf/cm^2	5.33	5.35	5.33	5.34	4.2	5.3
μ	0.378	0.377	0.378	0.377	0.425	0.379
$C = \dfrac{2R_1}{d_1}$	7.3					
A	5.9	5.9	5.9	5.9	3.9	5.9
Injector 2						
Re	26554	26554	14937	14937	22761	26554
Δp, kgf/cm^2	5.11	5.25	2.4	2.43	3.25	5.73
μ	0.0578	0.057	0.084	0.084	0.072	0.055
$C = \dfrac{2R_2}{d_2}$	4.8					
A	60.4	60.4	38.3	38.3	44.8	60.4

Depending on the shift of the faces of the injector's nozzles *a* (see Figure 3), injectors can be divided into **two groups**: the one of internal and external mixing of the components. Variation of the dimension *a* is not considered in this work while manufactured specimens are characterized as coaxial swirl injectors of external mixing. In case of external mixing the process is typically divided into two modes: independent operation of internal and external injectors (individual spray cones do not interact, see Figure 3a) and collaborative operation mode when spray cones interact near the nozzles and result in a common, single cone (see Figure 3b). The described operation modes can also change depending on the change of the environmental density (or pressure). The exact mode cannot be determined by simple hydraulic tests. Thus, to investigate more and find the main margins of the described effect, a complex equipment for advanced research is needed and, for this reason, the effect was not considered in this work [8–15].

In terms of a spray cone angle of the conventionally manufactured swirl injectors, there are known dependencies and their margins of application. The following dependencies are considered in the review [7]. Spray cone angles of additively manufactured swirl injectors were calculated and compared with experimental data. The results are shown in Table 3.

It can be seen from the Table 3, that the known dependencies for spray cone angle assessment cannot be used in case of additively manufactured swirl injectors. The discrepancy between calculated and experimental values lay beyond even the 10% interval, which is not acceptable for engineering applications.
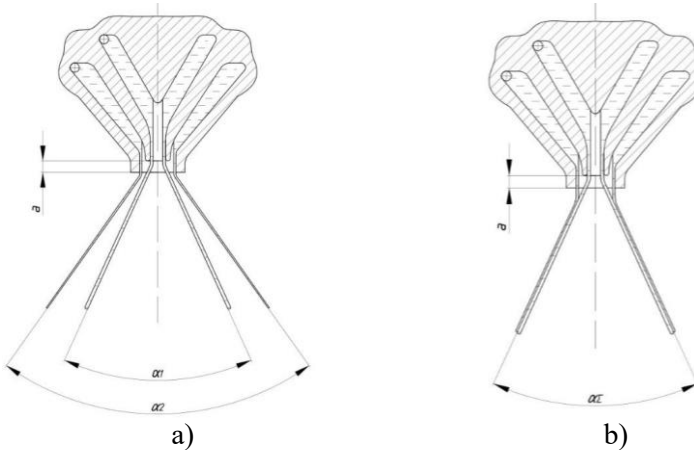
a)   b)

Figure 3 – Operational modes of coaxial swirl injectors
of external mixing

Table 3 – Experimental and calculated data on spray cone angle
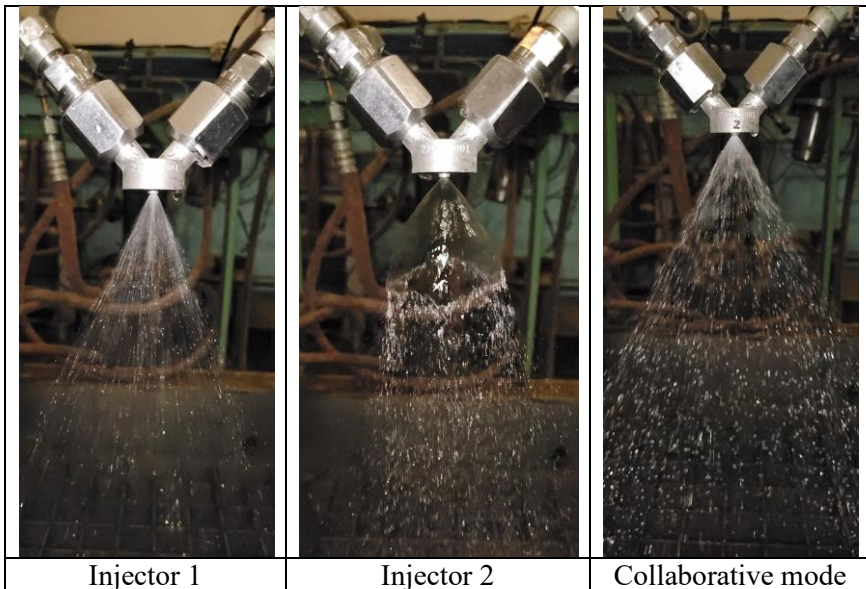of AM swirl injectors

Injector variant №	Experimental data	Benjamin [9]	Abramovich [8]	Fu et. al. [10]	Giffen and Muraszew [7]	Giffen and Muraszew (Liu et al. [7])	Khil et. al [13].	Liu et. al. [12]	Rizk and Lefebvre [7]	Xue et. al. [11]
Injector 1										
α_1, deg										
1	49.6	63.0	153.6	60.0	73.5	153.2	61.1	74.0	79.4	66.1
2	45.2	63.1	153.7	60.0	73.6	153.2	61.1	74.0	79.5	66.2
3	46.8	63.0	153.6	60.0	73.5	153.2	61.1	74.0	79.4	66.1
4	46.8	63.1	153.7	60.0	73.6	153.2	61.1	74.0	79.4	66.2
5	49.0	56.2	147.1	50.8	67.7	143.5	57.6	68.3	72.7	59.6
6	47.6	63.0	153.5	60.0	73.4	153.3	61.0	74.0	79.4	66.0
Injector 2										
α_2, deg										
1	76.2	122.0	178.0	114.9	128.5	170.1	105.1	92.7	134.5	115.9
2	70	122.2	178.0	114.9	128.8	170.0	105.6	92.7	134.9	116.1
3	76.6	104.0	176.8	98.7	121.0	168.0	90.7	90.5	115.5	111.1
4	71	104.1	176.9	98.7	121.1	167.9	90.9	90.5	115.7	111.3
5	77.8	110.3	177.4	107.5	124.2	168.6	96.2	91.3	122.3	110.9
6	77.2	122.9	178.1	114.9	129.6	169.7	107.4	92.7	136.2	116.7

At this moment, there is no known dependency describing the resulting spray cone angle of the additively manufactured coaxial swirl injectors of external mixing. It is due to the high complexity of the process that engineers must rely only on experimental data and preliminary results for obtaining more accurate data in terms of coaxial bipropellant swirl injectors. Experimental data describing resulting spray cone angle of the studied specimens is represented in Table 4. Obtained experimental data shows that collaborative operational mode is realized for each specimen. Photos of the operation of the specimen №2 is represented in Table 5.

Table 4 – Resulted spray cone angle of the additively manufactured coaxial bipropellant swirl injectors

Variant №	α_Σ, deg
1	56
2	55.2
3	55
4	56.6
5	57.6
6	56.4

Table 5 – Hydraulic testing of the injector (variant №2)

Injector 1	Injector 2	Collaborative mode

SUMMARY

With the purpose of investigation of the operation of additively manufactured coaxial bipropellant swirl injectors, 30 specimens were produced by L-PBF technology. As a material for injectors, a relatively easily accessible refractory alloy Haynes 230 was used. With the aim of determining the characteristics of injectors, numerous hydraulic tests were performed. According to the obtained data it found that:

– Repeatability of hydraulic characteristics of the manufactured injectors lay within 5% and is acceptable for further engineering purposes.

– Analysis of the known dependencies describing spray cone angle of the swirl injectors was carried out. The calculated values were compared to experimental data and there is a significant discrepancy between values.

– All calculated values of the spray cone angle of the individual operation mode show tendency to be larger than experimental data for each injector.

Currently there is no known dependency reliably describing the parameters of additively manufactured swirl injectors and further research is needed.

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