Numerical and Experimental Investigation on Dual Shear Coaxial Gas-Gas Injector

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Abstract： An investigation was conducted to evaluate possible performance enhance that can be achieved

By using dual shear coaxial configuration over a single shear coaxial injector arrangement, higher propellant flowrates per injection site was one of the focuses of this study because of the interest in reducing the number of injection sites. Current study shows that the dual shear coaxial injector was able to achieve much superior mixing performance over a single shear coaxial injector. Such gain in mixing performance could lead to high combustion efficiency over a shorter combustor length for future rocket engine combustors. Also the effect of design parameters of dual shear coaxial injector on combustion efficiency was investigated by both numerical simulation and experiments.

Key words： gas-gas injector; mass flowrate; combustion efficiency

Introduction Full Flow Stage Combustion (FFSC) cycle is one concept of the liquid rocket engine cycle for reusable vehicles, and gas-gas injector is one of the key technologies for the FFSC cycle engine[1]. In comparison with that of the traditional gas-liquid injector, the combustion limiting processes of atomization and vaporization of the gas-gas injector are eliminated, and the propellant mixing with chemical kinetics alone can control the rate of reaction and heat release. To make the propellant combust stably and efficiently and the heat load manageable are the main tasks for injector designers. The investigation on gas-gas injector was conducted extensively in America [2-4]. The Pennsylvania State University developed Raman Spectroscopy to measure the distribution of species in the combustor [5-9], and conducted numerical simulations to make a comparison with the experiment[10-12]. In order to develop an efficient design tool of injector, the research on gas-gas injectors has shed light on the heat flux of the combustor recently to improve the credibility of computational fluid dynamics[13-18]. Beijing University of Aeronautics and Astronautics has also conducted investigations on gas-gas injector[19-20], this paper describes their efforts on the gas-gas injector with large mass flow rate.

Developing an injector with large mass flow rate has high feasibility and practicability, as the way to reduce the cost of the injector’s head is to dramatically increase the individual element flow rate without decreasing the performance level of the injector. A joint technology program which is aimed at developing a high flow rate tricoaxial injection element has been conducted in France to Vulcain gas generator application[21]. Its result displays that the injection element with high mass flow rate is a way to reduce the cost of the injection head by reducing the number of the injection element. In order to reduce the cost of the engine, reducing the 208 injection elements of LE-5A engine to 127 injection elements is a significant step for Japan in the developing process of LE-5B engine[22], and the reduction of injection elements for LE-7A engine is an effective measure to meet the needs of cost requirements[23]. The combustion process of gaseous propellants is relatively simple since the problems of atomization and vaporization are eliminated; therefore, high combustion efficiency can be achieved logically when the injection element is at large mass flow rate.

The propellants are injected into the chamber in the form of hydrogen-oxygen-hydrogen by the dual shear coaxial injector, which is characterized by producing two shear combustion layers in the combustor, thus shortening the combustion length of propellants greatly. Though inducing the outer hydrogen to the central orifice can increase the complexity of the injector, it is still worthy to develop the potential applications of dual shear coaxial injectors. Based on the numerical simulations and experimental investigations in this paper, a comparison between the dual shear coaxial injector and the shear coaxial injector was conducted. The effect of the design parameters for the dual shear coaxial injector such as the oxygen injecting velocity, the velocity ratio of hydrogen to oxygen, as well as the mass flow ratio of the outer annulus to the central orifice on the characteristic combustion efficiency are investigated. Tests were also conducted to testify the performance of the dual shear coaxial injector element under the condition of large mass flow rate.

Numerical simulation model

With the standard k-ε model, the Full Navier-Stokes solutions are obtained for a gas-gas chamber. There are totally 7 species and 9 reactions that were taken into account in the finite rate chemistry model used for this computation. Axisymmetric assumptions were made to model the entire chamber from the injector face to the nozzle exit. The chemical reaction model was shown in table 1. Mass flow rates, species mass fractions and temperatures are specified at the inlets of the injector. The values of k and ε are specified based on a turbulence length scale. The flow is subsonic throughout the combustion chamber; at the outlet plane, all variables are extrapolated from the interior of the computational domain. All no slip walls are treated as adiabatic.

The evaluation method for simulation results

The chemical equilibrium is able to be achieved after the combustion of the oxygen and the hydrogen is completed in the chamber. The major combustion products are high temperature water, gaseous hydrogen and oxygen. For the propellants with a mixing ratio of 6, a chamber pressure of 3Mpa, and an initial temperature of 300K, a fuel-rich environment can be reached in the combustor finally. The results obtained from the Chemical Equilibrium Composition and Application Program (CECAP) display that the mass fraction of the hydrogen in the exhausted gas to its initial is 27.2%, and 2.0% for oxygen. The ratio of the amount of water in the products to the total mass flow rate is 85.2%.

The combustion location and the performance in the simulation for the gas-gas injector can be obtained by analyzing the axial distributions of the major species in the. At the location of x, the mass fraction of the ith specie can be expressed as:

□□□□□□□ $$\eta_i(x) = \frac{\int \phi_i \rho \vec{v} \, d\vec{A}}{m_i}$$

For hydrogen or oxygen, the m_i means the inlet mass flow rate, as well as the total propellants mass flow rate for water. ϕ_i is the mass fraction of the ith specie of a unit, ρ is the density, $\vec{v}$ and $\vec{A}$ represent the vectors of velocity and area of a unit, respectively. Besides, a comparison of the theoretical values of the products with the results obtained from the numerical simulations at the nozzle exit is made to investigate the combustion efficiency The more closer the numerical result is to the theoretical values, the better combustion efficiency can be achieved.

In this paper, the Space Shuttle Main Engine (SSME) injector is adopted for reference, since the “large mass flow rate” is a relative concept. With the constant mass flux and the fixed chamber pressure of 3MPa, an investigation was conducted in order to evaluate the performance of the dual shear injector. The characteristic length of the chamber was set to be 800mm, which is the same as that of the SSME. The nozzle convergency ratio is 3.1. Those are determined by using the total mass flow rate of the injector divide by the number of the injectors so as to obtain the mass flow rate of the unit injector; as the chamber pressure is proportional to the mass flow rate in the chamber, so the mass flow rate of the unit injector needs to be transformed to a low chamber pressure for the convenience of experiments. When the chamber pressure is 3MPa, the mass flow rate per unit injector is 0.113kg/s. The design parameters for the SSME engine are summarized in Table 2.

When the mass flow rate varies in a certain range with the chamber pressure being 3MPa, the mass flux in the chamber is required to be constant, which means that the ratio of the mass flow rate to the cross sectional area of the chamber remains constant. However, the actual mass flux has slightly difference from the objective value due to the constraint of the combustor fabrication. The design parameters for the experimental combustor are shown in Table 3.

Comparison with the shear coaxial injector

Numeric simulations were conducted on the shear coaxial injector combustor with the mass flow rate being 0.226kg/s, 0.332kg/s and 0.452kg/s respectively. The simulation results were then compared with those of the dual shear coaxial injector. The design parameters for both injectors were the same, in which the oxygen outlet velocity was 39.3m/s, the velocity ratio was 9, and the injector post thickness was 1.5mm.

Fig. 1 represents the water concentration distribution in the chamber for the traditional shear coaxial injector. It can be seen that the mixing and the combustion of the propellants are limited by the thin shear layer between the two propellant flows at the forepart of the chamber. The steep propellant concentration gradients can be seen in the shear layer. At a further downstream location, the water concentration distribution in the chamber would keep away from the injector plate as the mass flow rate increases, which means that the propellants need a longer chamber length to reach a high combustion efficiency.

Fig. 2 is the axial distribution curves of the water mass fraction for different mass flow rates. It shows that the mass fraction of water increases along the axial direction. Moreover, at the same axial location, the water mass fraction in the chamber is definitely lower for large mass flow rate compared to that for a smaller one.

As shown in Table 4, when the mass flow rate is 0.452kg/s, the mass fraction of each major species is 0.841 for water, 0.29 for hydrogen and 0.051 for oxygen at the exit of nozzle. The result indicates that for the traditional shear coaxial injector the propellants cannot achieve an efficient combustion under the condition of an excessive mass flow rate, with the mass flux being fixed.

Fig. 3 represents the numerical result of the dual shear coaxial injector with the mass flow rate of 0.452kg/s and the central hydrogen ratio of 0.3. As shown in Fig.3, the propellants are injected in a pattern of oxygen-hydrogen-oxygen from the dual shear coaxial injector. The outer hydrogen through the annulus forms a fuel-rich zone, which has a benefit as the heat shield of the faceplate and the chamber wall.

Besides, two shear layers can be observed in the chamber, and two reaction layers were formed in the forepart of the chamber. As the Oxygen and the hydrogen are mixed and then react in the chamber, the chemical energy is released gradually. Once the two propellants contact each other the reaction starts immediately, and a continuous combustion flame can be formed. The results of the numerical simulation demonstrate that the dual shear coaxial injector can perform the propellants combustion in a short axial length.

Fig. 4 represents the axial distributions of the water mass fraction in the chamber for the two types of injectors. It can be seen that the axial distribution curve for the traditional shear coaxial injector is relatively smooth, which means that the propellants are consumed slower compared to that of the dual shear coaxial injector, and a relatively longer chamber length is thus required. The water mass fraction of the dual shear injector is larger than that of the shear coaxial injector at the same axial location. As the dual shear coaxial injector consumes both oxygen and hydrogen, so that water can be generated simultaneously in a relatively shorter axial distance. Thus, the dual shear coaxial injector has the potential to make the propellant achieve high combustion efficiency under the condition of large mass flow rates.

Numerical analysis of the dual shear coaxial injector

Numeric simulation was conducted to investigate the performance of the dual shear coaxial injector with the chamber pressure remaining 3MPa and the propellants mixing ratio of 6. The design parameters include: the injector mass flow rate, the oxygen injection velocity, the velocity ratio of the hydrogen to the oxygen, and the ratio of the hydrogen mass flow rate of the central orifice to the total hydrogen mass flow rate. In this paper, the selected design parameters vary in a certain range, while other parameters keep constant.

The effect of oxygen injection velocity on combustion process

The oxygen injection velocity is an important design parameter for the dual shear coaxial injector. Generally, the injection velocity for liquid oxygen is about 30m/s. Numerical simulations were conducted on the dual shear coaxial injector to analyze the effect of the oxygen injection velocity on the combustion process in this paper. The design parameters of the dual shear coaxial injector are listed in Table 5, and the scheme of the dual shear coaxial injector is shown in Fig.5.

Fig. 6 represents the axial distributions of the major species in the chamber of the dual shear coaxial injector with various oxygen injection velocities. At the same axial location, it can be seen that as the oxygen injection velocity increases, the mass fractions of hydrogen and oxygen decrease, while the mass fraction of the water rises. This illustrates that a higher oxygen injection velocity is a preferable choice for the dual shear coaxial injector which has a benefit to the chemical reaction. Additionally, at the axial location of 210mm from the faceplate, only little difference is observed on the mass fraction of the major. This indicates a perfect combustion of the propellants in the chamber.

The effect of velocity ratio on combustion process

A velocity difference is necessary for the propellants which is benefit to the mixing effect of the propellants. Generally, O2 jet with a slow velocity and H2 jet with a high velocity through the dual shear coaxial injector are to be chosen. The hydrogen flow with a high velocity mixes with the oxygen jet through the shear interaction, and the velocity ratio is thus a key factor in determining the position of the shear layer where the propellants mix and react. In this paper, simulations were conducted to investigate the effect of the velocity ratio variation on the combustion performance. The design parameters of the dual shear coaxial injector with different velocity ratios are listed in Table 6.

Fig. 7 shows the axial distribution of the major species in the chamber of the dual shear coaxial injector with different velocity ratios. It can be seen that the axial profiles in the chamber vary significantly with the change of the velocity ratio, and the mass fraction of oxygen and hydrogen is low while the mass fraction of water is high at the same axial location. This tendency grows more apparent while the velocity ratio increases from 3 to 7; however, the trend is not so obvious while the velocity ratio increases from 9 to 11. This demonstrates that the velocity ratio of hydrogen to oxygen is an important design parameter for the dual shear coaxial injector, and the increase of the velocity ratio can prompt the performance of mixing and the chemical reaction of propellants. But an immoderate increase of the velocity ratio can only result in a weak effect on the combustion performance, which is also detrimental to the propellants' supply system.

Table 7 shows the major species mass fraction with different velocity ratios at the nozzle exit. Note that the mass fraction of the major species is similar to the result of CECAP except for the case with a velocity ratio of 3, which indicates that the propellants are not completely consumed in the chamber. Under other conditions, the mass fraction of the species differs slightly from the result of CECAP due to higher velocity ratios. This demonstrates that the velocity ratio of the propellant can affect the combustion performance effectively.

The effect of central hydrogen mass flow rate ratio on combustion process

It is required for the dual shear coaxial injector to induce a hydrogen jet to the central orifice , so that the propellants can form two shear layers. The central hydrogen mass flow rate ratio is defined as the hydrogen mass flow rate of the central orifice to the hydrogen mass flow rate of the unit injector, which is a unique design parameter for the dual shear injector. The central hydrogen mass flow rate ratio is varied by changing the area ratio of the central orifice to the outer annulus. The design parameters of the injector are listed in Table 8. The outlet dimension of the dual shear coaxial injector is shown in Table 9. It can be seen that the variation of the central hydrogen mass flow rate ratio has an influence on the dimension of the injector slightly.

Fig. 8 is the temperature distribution with different hydrogen mass flow rate ratios in the chamber. It means that the variation of the hydrogen mass flow rate ratio can lead to a drastic difference in the temperature distribution. When the central hydrogen mass flow rate ratio is 0.2, the low temperature zone of the central hydrogen jet disappears at the axial location of 160mm from the faceplate, and the flame is close to the centerline. With the increase of the central hydrogen mass flow rate ratio, the length of the central low temperature zone extends. When the central hydrogen mass flow rate ratio is 0.5, the central low temperature zone nearly extends to the exit of the nozzle. This means that the change of the central hydrogen mass flow rate ratio can impact the temperature distribution significantly in the chamber for the dual shear coaxial injector.

The OH concentration is a reasonably accurate marker for flame, and its distribution can predict the location of the chemical reaction in the chamber. The OH concentration distributions of different central hydrogen mass flow rate ratios are given in Fig. 9. It can be seen that the ratio of the central hydrogen mass flow rate can affect the OH concentration distribution obviously. The OH concentration mainly spreads between the O_2 and the H_2 streams in the case that the central hydrogen mass flow rate ratio reaches 0.3 or 0.4, which implies that the location of the chemical reaction is just between those two streams. And the lower (or higher) central hydrogen mass flow rate ratio can cause the reaction location incline to the chamber wall (or centerline). This numerical prediction shows that the chemical reaction location in the chamber can be determined by the central hydrogen mass flow rate ratio .

The axial distributions of the water with varied central hydrogen mass flow rate ratio are shown in Fig. 10. To be noted that the central hydrogen mass flow rate ratio has an impact on the water axial curves. This simulation result also indicates that the central hydrogen mass flow rate ratio can influence not only the location of the chemical reaction but also the combustion efficiency. A reasonable design for the dual shear coaxial injector is to make the best use of the two shear mixing layers, so that a good combustion efficiency can be achieved.

The effect of mass flow rate ratio on combustion process

The dual shear coaxial injector has the potential to achieve high combustion efficiency on the condition of large mass flow rates. Some Investigations on the mass flow rates varying from 0.678kg/s to 1.13kg/s were conducted with the a constant mass flux. The injector design parameters are summarized in Table 10, and the related combustor design parameters are given in Table 3.

The contours of the water mass fraction shown in Fig. 11 depicts that the spray distance of the O2 and H2 jet becomes longer from the faceplate towards downstream with the increase of the mass flow rate, and the resultant water distribution prolongs an axial distance relatively. The zone predominated by water is in the nozzle section when the mass flow rate is 1.13kg/s.

The axial mass fraction curves of the water for different mass flow rates as given in Fig. 12 indicate that all the curves have similar shapes. The water mass fraction is relatively low for large mass flow rates at any axial location on the downstream. These results demonstrate that the propellants require a relatively long axial length to be completely consumed in the chamber if the injector has a large mass flow rate.

Table 11 displays the major species mass fraction at the nozzle exit of the injectors with different mass flow rates. It can be seen that the mass fractions of the major species differ apparently from the result of CECAP with the mass flow rate of 1.13kg/s, which indicates an incomplete combustion of the propellants. Under other conditions, the mass fractions of the major species have a good agreement with the results of CECAP. This illustrates that the propellants can achieve high combustion efficiency with the mass flow rate of 1.017kg/s, which is as nine times great as the mass flow rate of a single SSME injector.

Experimental investigation

Experiments were conducted to validate the performance of the dual shear injector with large mass flow rates. The duration of the test is 3 seconds. The chamber is made up of red copper, and the injector is made up of stainless steel. The pneumatic resonance ignitor is adopted to ignite the propellants. Fig. 13 represents a sketch of the combustor assembly, and Fig. 14 shows the picture of the combustor assembly being installed on the test bed. The pressure and the flow rate in the chamber were measured to calculate the values of the characteristic velocity and the characteristic efficiency, which can be used for the performance comparisons. The temperatures at different locations in the combustion chamber and on the injector face were measured to calculate the heat load of the chamber.

Fig. 15 is a schematic of the dual shear coaxial injector. It can be seen that the outer hydrogen is induced to the central orifice through three radial orifices, and the total area of the three radial orifices is two times larger than that of the central hydrogen orifice. The control of the hydrogen mass flow rate ratio is implemented by changing the outlet areas of the central hydrogen orifice and outer annulus. Oxygen is fed to the oxygen outlet through three fan-shaped orifices which can be fabricated by the wire electrode cutting.

Hot fire tests were performed to study the influence of the central hydrogen mass flow rate ratio on the combustion efficiency with the mass flow rate of 0.678kg/s. Tests with the nominal mass flow rate increasing from 0.425kg/s to 0.904kg/s were conducted to validate the performance of the dual shear coaxial injector on the condition of large mass flow rates, while the central hydrogen mass flow rate ratio remains to be 0.3. Fig. 16 shows the picture of a dual shear injector after the hot fire experiment. It can be seen that the ablation did not occur, which demonstrates that acceptable heat load can be achieved by the dual shear coaxial injector.

The mass flow rate in the experiment was controlled by the sonic throat, which was calibrated by a high precise mass flowmeter. The relational graph between the pressure before the sonic throat and the mass flow rate was plotted before the tests. The pressure and the temperature before the sonic throat was measured and collected in the test to calculate the mass flow rate.

Fig. 17 shows the pressure curves of the experiment with a mass flow rate of 0.452kg/s. It can be seen that the ignitor maintains 1 second, the hydrogen is then injected into the chamber, and the pressure of the hydrogen sonic throat rises subsequently. At the fourth second, oxygen is injected into the chamber, and the chamber pressure rises promptly. The duration of the test is 3 seconds, and at the time of 7.2 second the main oxygen valve is shut up, and the chamber pressure drops instantly. The test ends once the main hydrogen valve is shut up at the time of 9.5 second. Note that the ignitor chamber pressure and the pressure on the upstream of the injector are higher than those of the main chamber, which demonstrates that the experiment was conducted successfully.

Table 12 is the collected data from the three experiments for the dual shear coaxial injector with the nominal mass flow rate of 0.452kg/s. It can be seen that the collected data in the tests are consistent with the design values. As shown in Table 13, the characteristic efficiencies of the propellants for all the three tests reached at about 96.2%. Those three characteristic efficiencies are not very high since the heat sinking chamber is adopted in these tests, which absorbs a certain amount of heat energy, thus causing the decrease of the characteristic efficiency.

Analysis of the characteristic efficiency

Fig. 18 represents the experimental results for different central hydrogen mass flow rate ratios, and other injector design parameters are shown in Table 7. When the central hydrogen mass flow rate ratio is 0.2, the characteristic efficiency can reach around 94%. However, when the central hydrogen mass flow rate ratio is between 0.3 and 0.4, the characteristic efficiency reaches 96%, so that a good efficiency is then achieved. It can be concluded that the combustion characteristic efficiency is affected by the central hydrogen mass flow rate ratio, and a lower central hydrogen mass flow rate ratio can lead to worse combustion efficiency.

Fig. 19 shows the characteristic combustion efficiency of the dual shear coaxial injector with different mass flow rates, and other design parameters for the injector are shown in Table 9. As shown, the characteristic combustion efficiency is between 96% and 97% for the injector with different mass flow rates. Besides, when the nominal mass flow rate reaches 0.904kg/s, the characteristic efficiency is still around 96.3%, which implies that the dual shear coaxial injector can make the combustion of the propellants more efficient under the condition of large mass flow rates which is almost as eight times great as that of a single Space Shuttle Main Engine (SSME) injector. In addition, due to the adoption of the heat sinking chamber in this paper, a certain amount of heat energy can be absorbed that leads to an unnecessarily of the cooling system. However, it also causes a decrease of chamber pressure in the experiment, which makes it impossible for the calculated characteristic combustion efficiency to reach 100%.

Conclusion

Based on the numerical simulations and experiments presented in this paper, the following observations can be made:

(1) The potential to increase the mass flow rate of the traditional injector is limited, as the shear coaxial injector makes the combustion location far away from the faceplate with the increase of the mass

flow rate.

(2) The dual shear coaxial injector can produce two combustion layers in the chamber. The central hydrogen mass flow rate ratio is an important parameter for this injector. When the central hydrogen mass flow rate ratio is between 0.3 and 0.4, the injector can make the best use of those two shear mixing layers to achieve high combustion efficiency.

(3) The dual shear coaxial injector can shorten the combustion length of propellants significantly, and a high combustion efficiency of the propellants can be achieved when the mass flow rate is almost as eight times large as that of a single SSME injector.

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Table 1 O2-H2 chemical reaction model

No.	Chemical reaction
1	H2+O2=OH+OH
2	OH+H2=H2O+H
3	H+O2=OH+O
4	H2+O=OH+H
5	H2O+O=OH+OH
6	H+H+M =H2+M
7	H+OH+M =H2O+M
8	H+O+M =OH+M
9	O+O+M =O2+M

Table 2 Injector design parameters of SSME engine

Chamber pressure / MPa	Mass flowrate of the injector/（kg/s）	Number of injector elements	Mass flowrate of the single element/（kg/s）
20.7	469	600	0.78

Table 3 Design parameters of combustor

Mass flowrate /(kg/s)	Diameter of chamber /m	Diameter of nozzle throat /m	Mass flux /[kg/(s·m^2)]
0.113	0.0184	0.104	425
0.226	0.026	0.0148	426

0.339	0.0319	0.0181	424
0.452	0.0368	0.0208	425
0.565	0.0412	0.023	424
0.678	0.0451	0.0256	425
0.791	0.0486	0.0277	427
0.904	0.052	0.0296	426
1.017	0.0552	0.0312	425
1.130	0.0582	0.0329	425

Table 4 Major species mass fraction of the shear coaxial injector at the exit of the nozzle

Simulation results	Mass fraction of species		
	Water	Hydrogen	Oxygen
Result of CECAP	0.852	0.272	0.02
Mass flowrate：0.226kg/s	0.852	0.26	0.02
Mass flowrate：0.339kg/s	0.849	0.264	0.024
Mass flowrate：0.452kg/s	0.841	0.29	0.051

Table 5 Design parameters of the dual shear coaxial injector with different oxygen injection velocity

Design parameter	value
Mass flowrate(kg/s)	0.452
The ratio of the hydrogen mass flowrate in the central	0.3

orifice to that in the outer annulus	
Oxygen injection velocity (m/s)	39.3, 67.6, 86.8, 102,115
Corresponding ratio of oxygen drop to chamber pressure	1%,3%,5%,7%,9%
Injector post tip thickness (mm)	1.5
Velocity ratio of hydrogen to oxygen	9

Table 6 Design parameters of the dual shear coaxial injector with different velocity ratio

Design parameter	value
Mass flowrate(kg/s)	0.678
The ratio of the hydrogen mass flowrate in the central orifice to that in the outer annulus	0.3
Oxygen injection velocity (m/s)	67.6
Injector post tip thickness (mm)	1.5
Velocity ratio of hydrogen to oxygen	3, 5, 7, 9, 11

Table 7 Major species mass fraction with different velocity ratio at the nozzle exit

Simulation results	Mass fraction of species		
	Water	Hydrogen	Oxygen
Result of CECAP	0.852	0.272	0.020
Velocity ratio of 3	0.847	0.287	0.032
Velocity ratio of 5	0.853	0.276	0.024

Velocity ratio of 7	0.854	0.274	0.023
Velocity ratio of 9	0.854	0.274	0.022
Velocity ratio of 11	0.855	0.272	0.022

Table 8 Design parameters of the dual shear coaxial injectors with different hydrogen mass flowrate ratio

Design parameter	Value
Mass flowrate(kg/s)	0.678
Oxygen injection velocity (m/s)	67.6
Injector post tip thickness (mm)	1.5
Velocity ratio of hydrogen to oxygen	9
The central hydrogen mass flowrate ratio	0.2,0.3,0.4,0.5

Table 9 Outlet dimension of the dual shear coaxial injector with different hydrogen mass flowrate ratio

Central hydrogen mass flowrate ratio	d /mm	dout /mm	D /mm
0.2	5.98	25.38	30.8
0.3	7.32	25.89	31.0
0.4	8.45	26.36	31.13
0.5	9.45	26.8	31.27

Table 10 Design parameters of the dual shear coaxial injector with varied mass flowrates

Design parameter	values
Oxygen injection velocity (m/s)	67.6
Injector post tip thickness (mm)	1.5
Velocity ratio of hydrogen to oxygen	9
The hydrogen mass flowrate ratio of the central orifice	0.3
Mass flowrate (kg/s)	0.678, 0.791, 0.904, 1.017, 1.13

Table 11 The major species mass fractions at the nozzle exit for the injectors with different mass flowrates

Simulation results	Mass fraction of species		
	Water	Hydrogen	Oxygen
Result of CECAP	0.852	0.272	0.020
Mass flowrate 0.678kg/s	0.853	0.276	0.024
Mass flowrate 0.791kg/s	0.853	0.277	0.024
Mass flowrate 0.904kg/s	0.852	0.278	0.026
Mass flowrate 1.017kg/s	0.851	0.28	0.028
Mass flowrate 1.13kg/s	0.840	0.289	0.037

Table 12 Test data for the injector with the nominal mass flowrate being 0.452kg/s

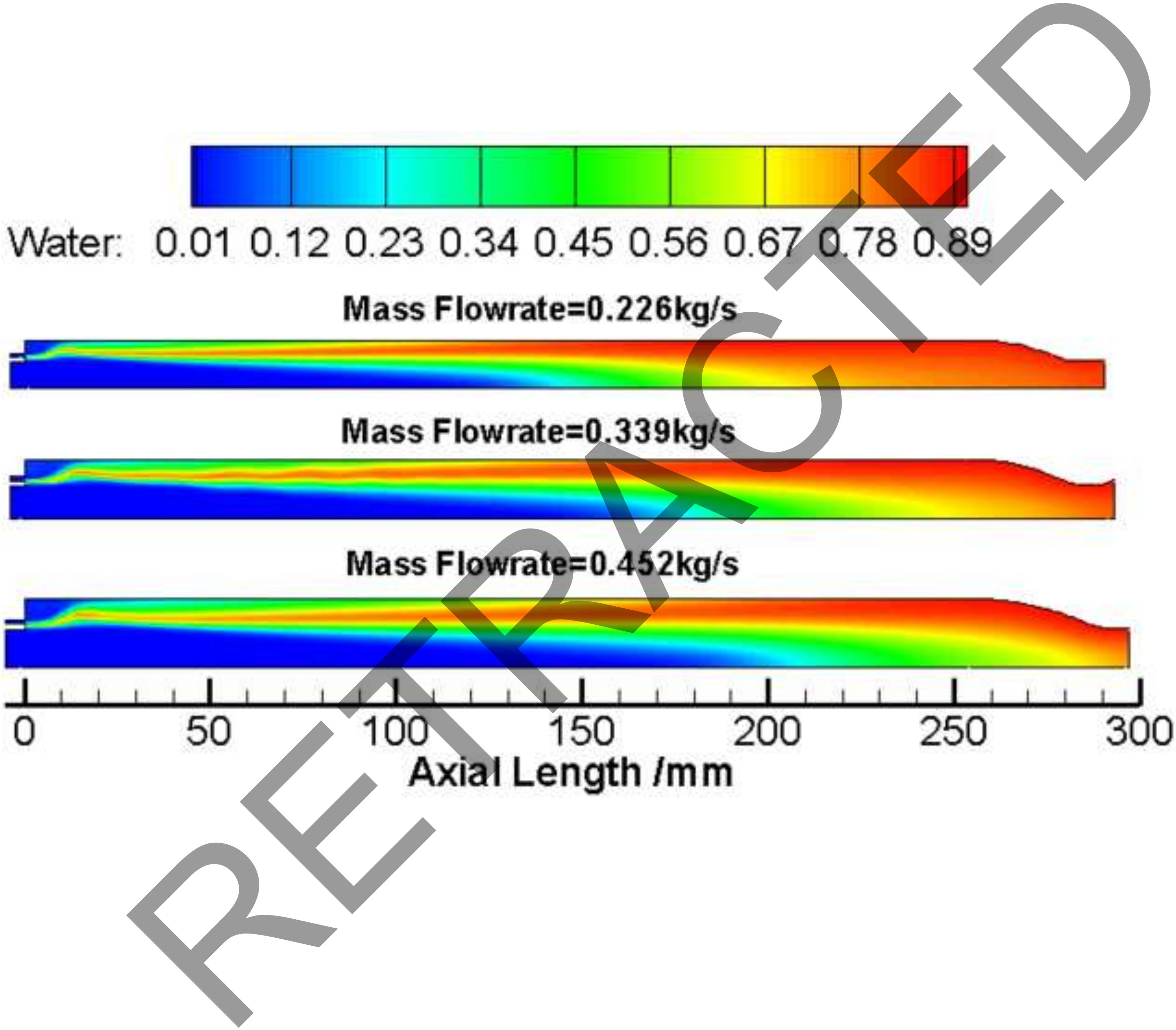
Propellant	Diameter of sonic throat /mm	Pressure upstream the sonic throat /MPa	Temperature of propellant/。C	Mass flowrate /（kg/s）

Hydrogen	4.6	6.20	-3	0.0654
		6.18	-2	0.0651
		6.14	-1.5	0.0643
Oxygen	5.7	6.07	-3.0	0.3897
		6.01	-0.6	0.3855
		6.04	-1.2	0.3875

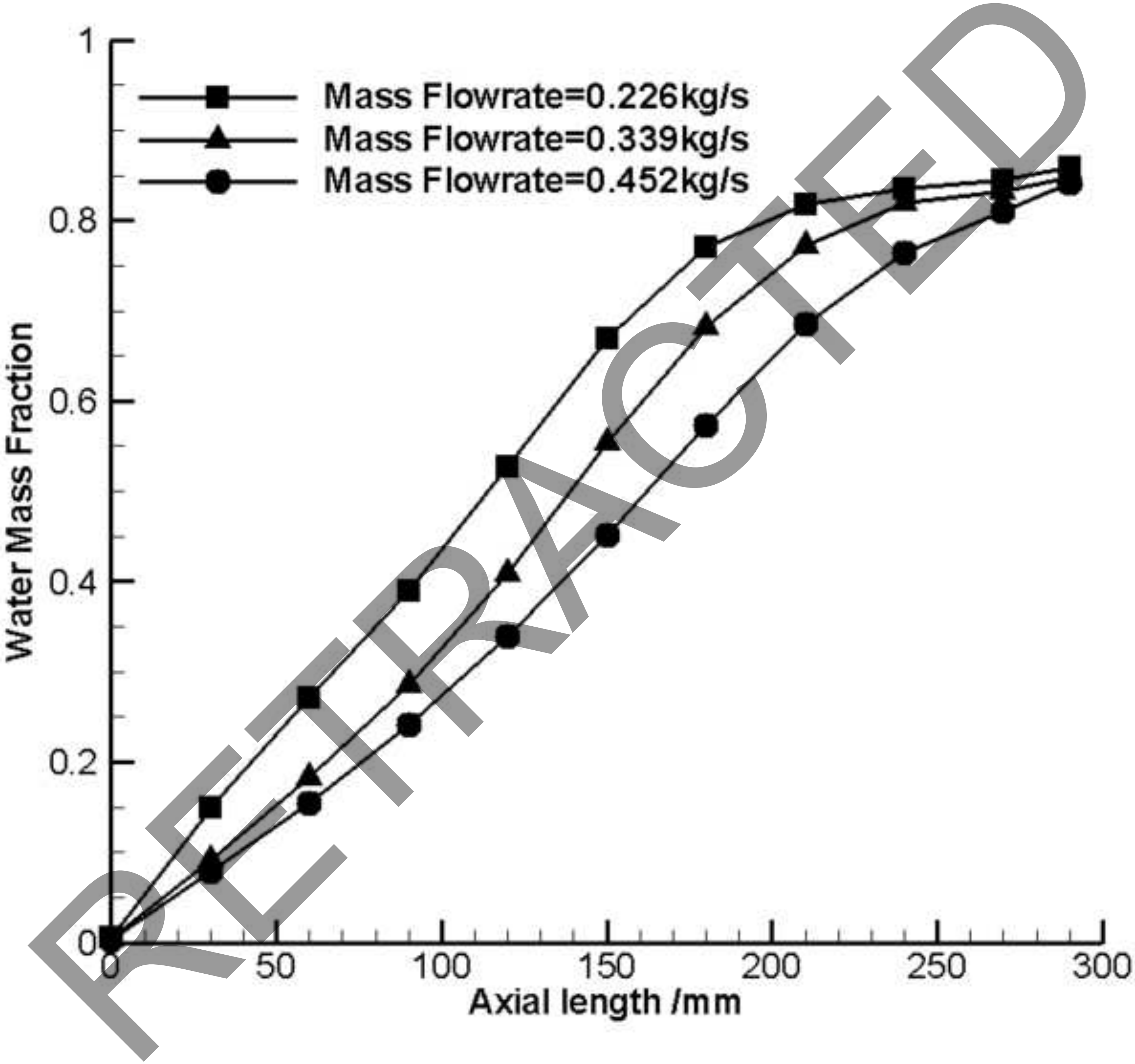
Table 13 Characteristic efficiency of the three tests for the injector with the nominal mass flowrate being 0.452kg/s

Chamber pressure /MPa	Mass flowrate of propellants /(kg/s)	Mix ratio	Experimental characteristic velocity /(m/s)	Theoretical characteristic velocity /(m/s)	Characteristic efficiency
2.98	0.455	5.96	2224.1	2312	0.962
2.95	0.4506	5.92	2223.4	2316	0.960
2.96	0.4518	6.03	2225	2305.6	0.965

Figure

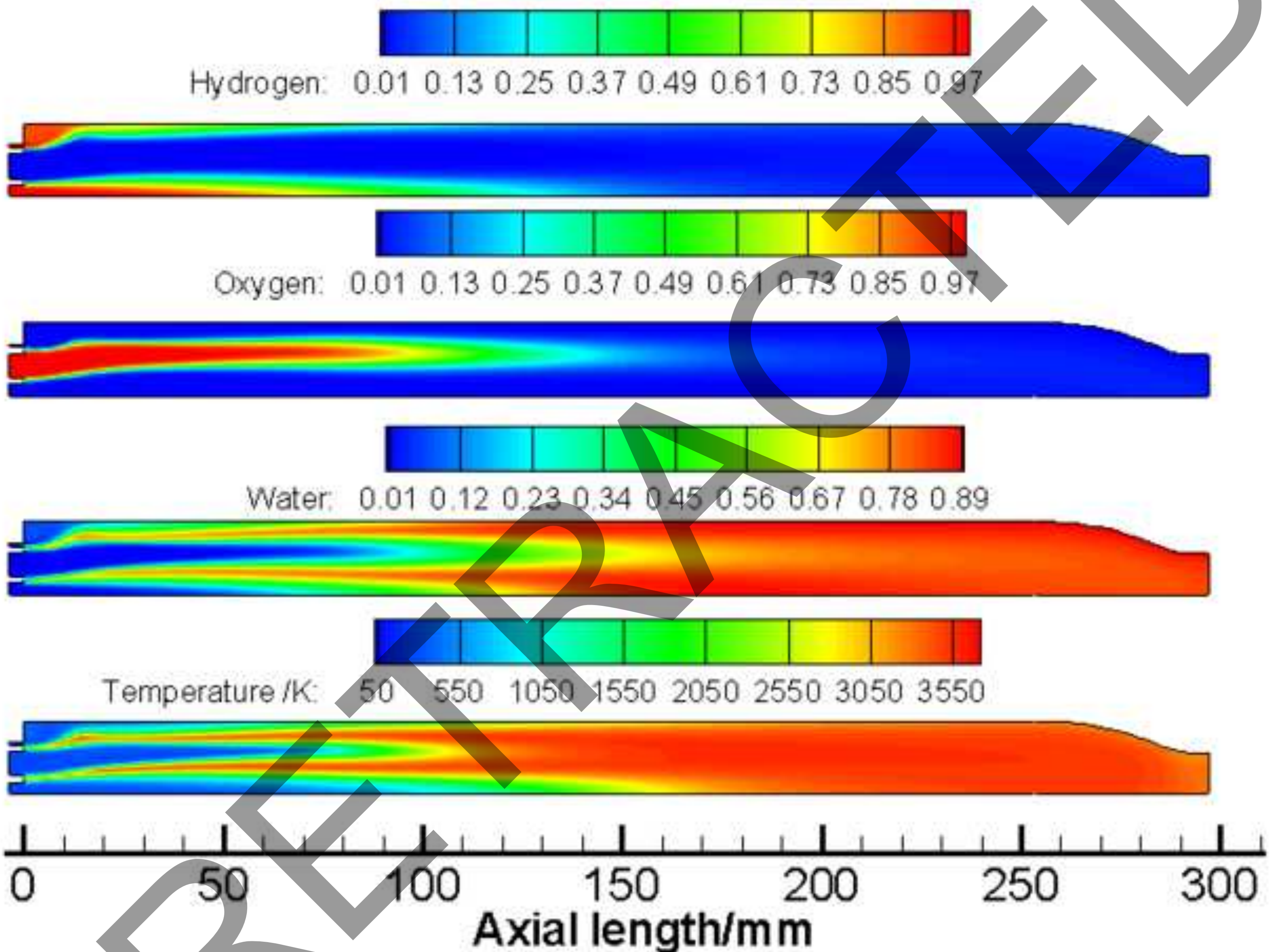

Water: 0.01 0.12 0.23 0.34 0.45 0.56 0.67 0.78 0.89
Mass Flowrate=0.226kg/s
Mass Flowrate=0.339kg/s
Mass Flowrate=0.452kg/s
0 50 100 150 200 250 300
Axial Length /mm
RETRACTED

Figure

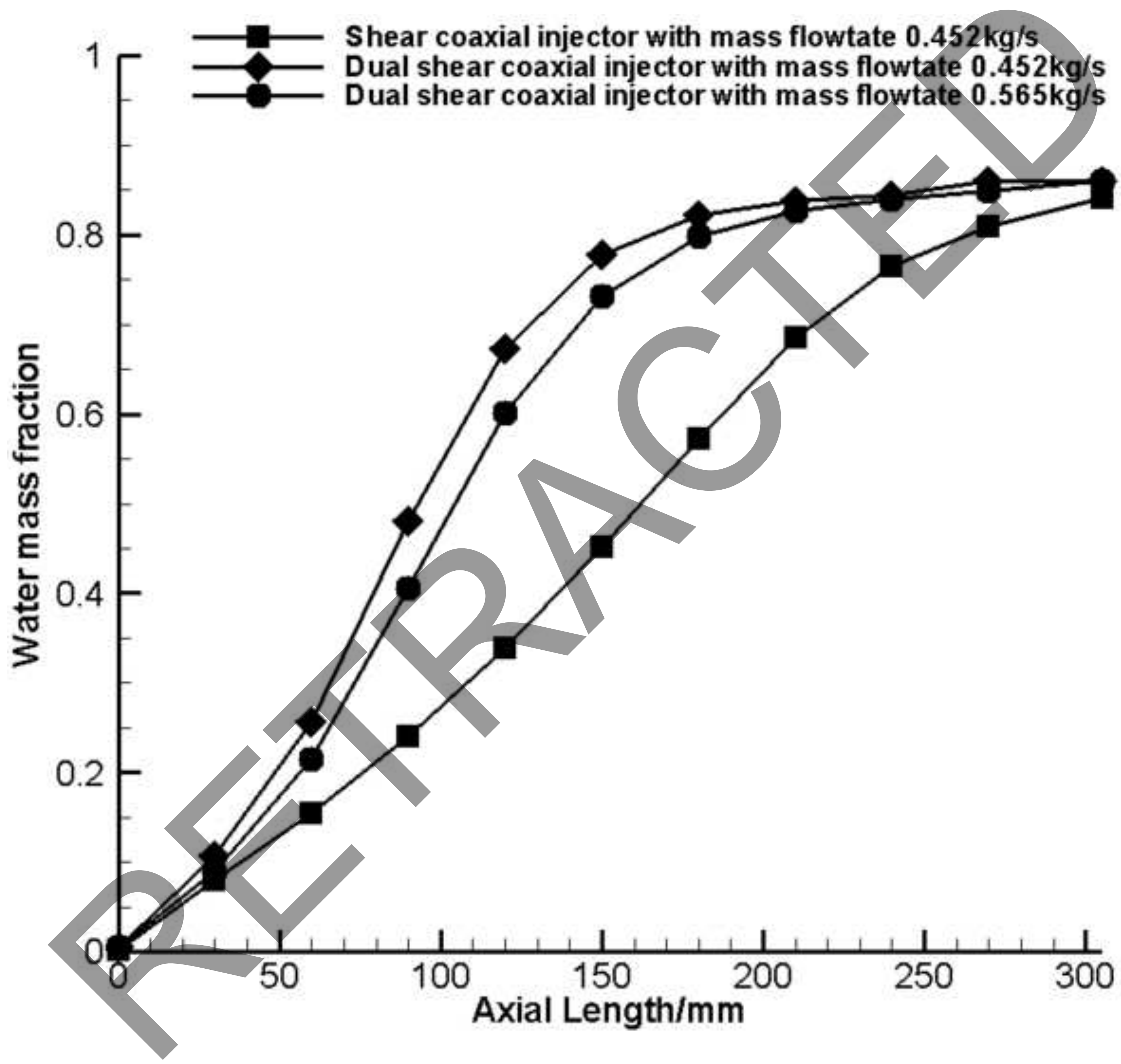


Mass Flowrate=0.226kg/s
Mass Flowrate=0.339kg/s
Mass Flowrate=0.452kg/s
Water Mass Fraction
Axial length /mm
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
RETRACTED

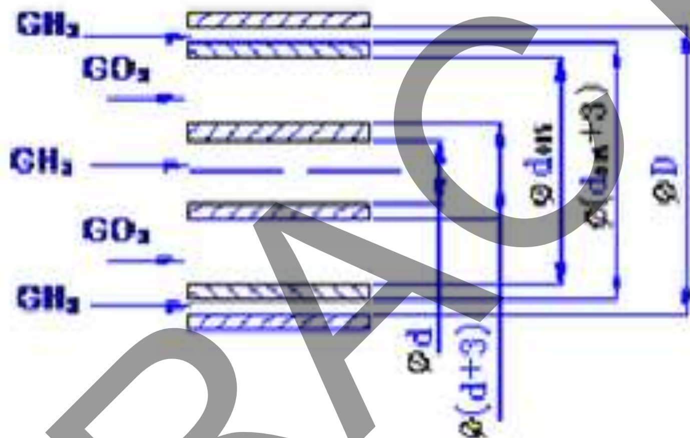
Figure


Hydrogen: 0.01 0.13 0.25 0.37 0.49 0.61 0.73 0.85 0.97
Oxygen: 0.01 0.13 0.25 0.37 0.49 0.61 0.73 0.85 0.97
Water: 0.01 0.12 0.23 0.34 0.45 0.56 0.67 0.78 0.89
Temperature /K: 50 550 1050 1550 2050 2550 3050 3550
0 50 100 150 200 250 300
Axial length/mm

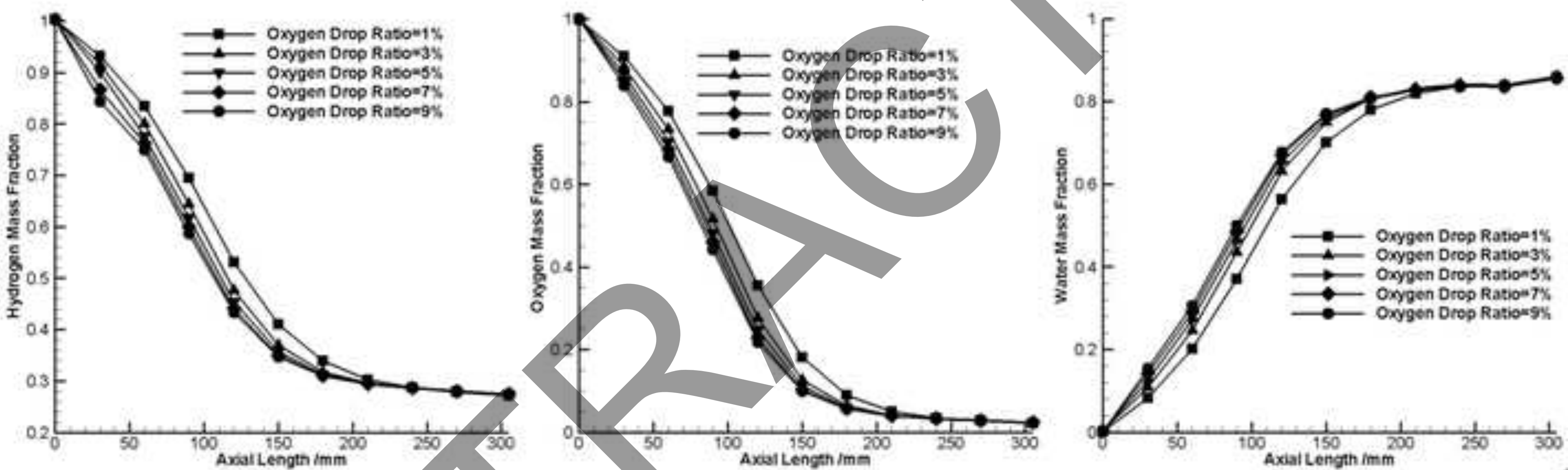
Figure


Shear coaxial injector with mass flowtate 0.452kg/s
Dual shear coaxial injector with mass flowtate 0.452kg/s
Dual shear coaxial injector with mass flowtate 0.565kg/s
Water mass fraction
Axial Length/mm
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
RETRACTED

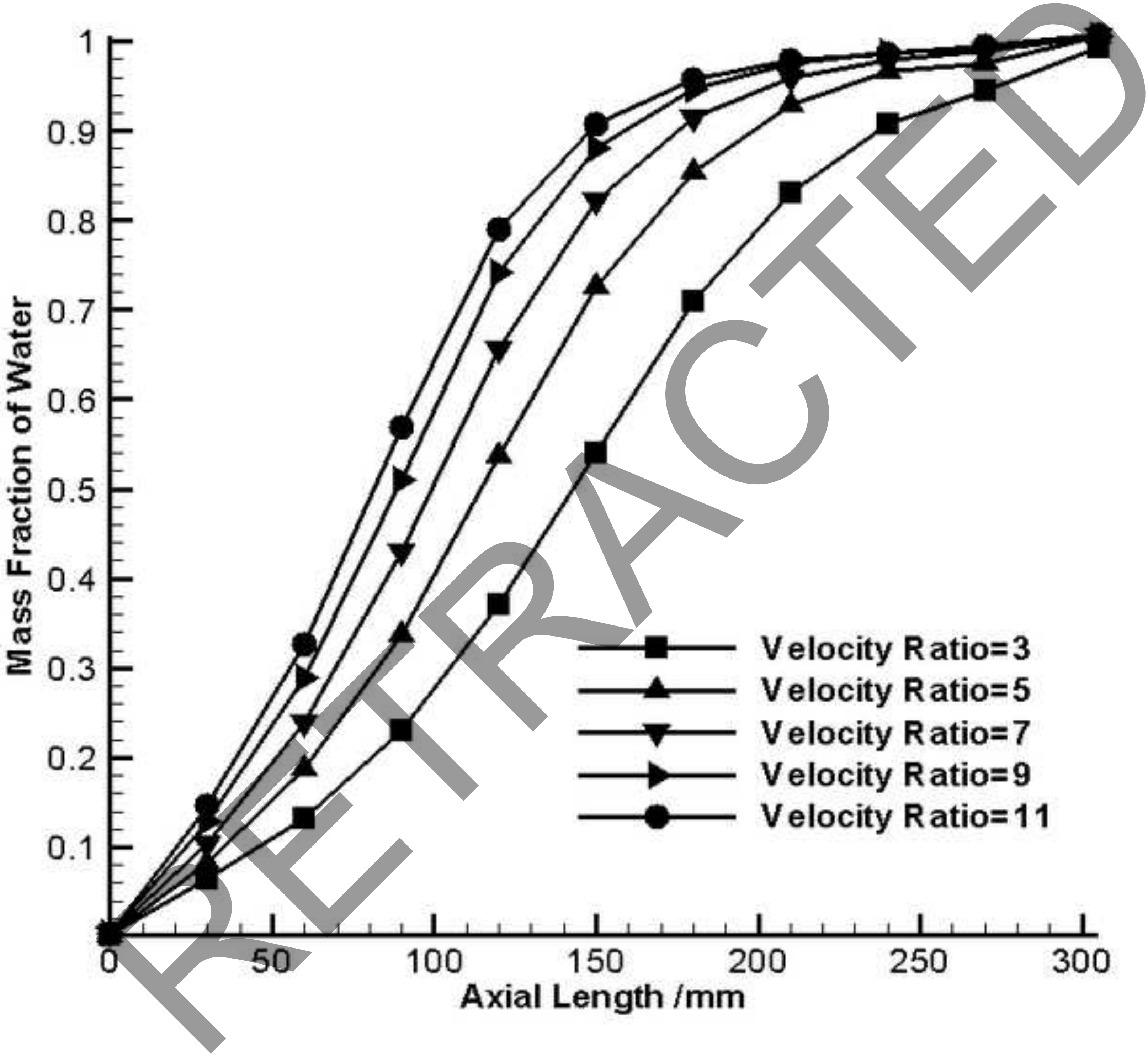
Figure



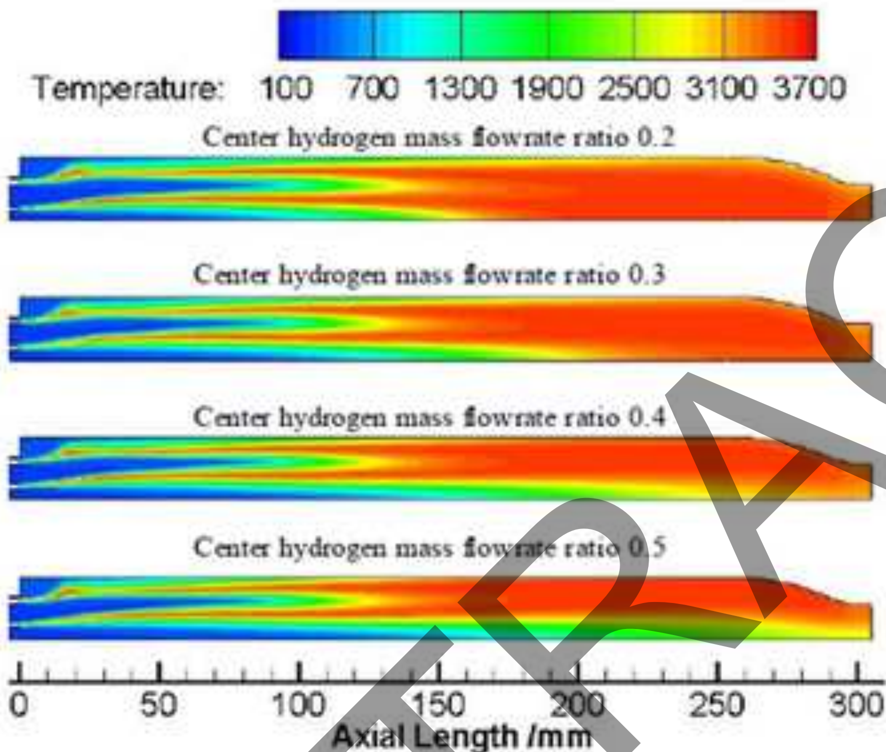
Figure


Oxygen Drop Ratio=1%
Oxygen Drop Ratio=3%
Oxygen Drop Ratio=5%
Oxygen Drop Ratio=7%
Oxygen Drop Ratio=9%
Hydrogen Mass Fraction
Axial Length /mm
Oxygen Mass Fraction
Water Mass Fraction

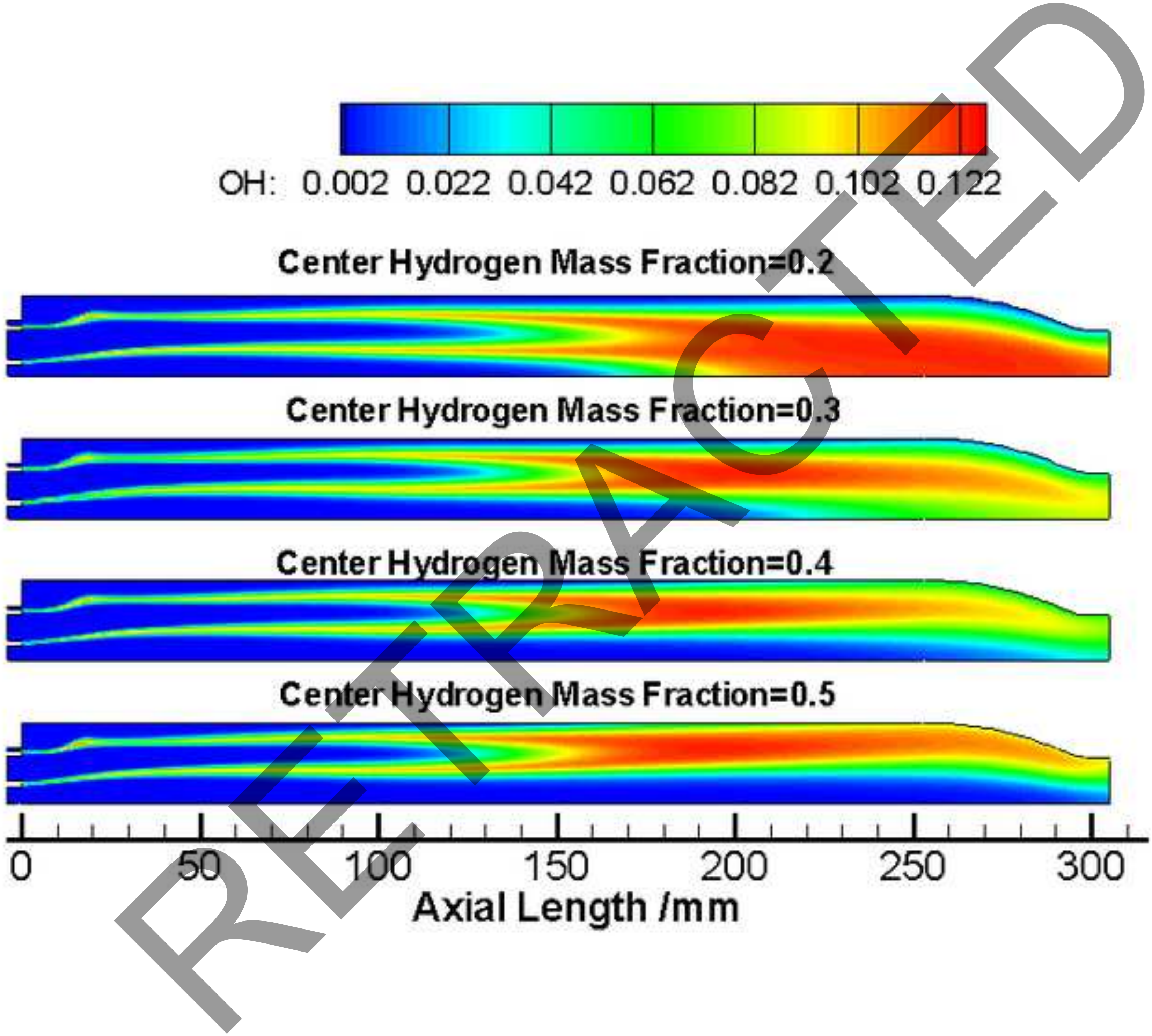
Figure


Mass Fraction of Water
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50
100
150
200
250
300
Axial Length /mm
Velocity Ratio=3
Velocity Ratio=5
Velocity Ratio=7
Velocity Ratio=9
Velocity Ratio=11
RETRACTED

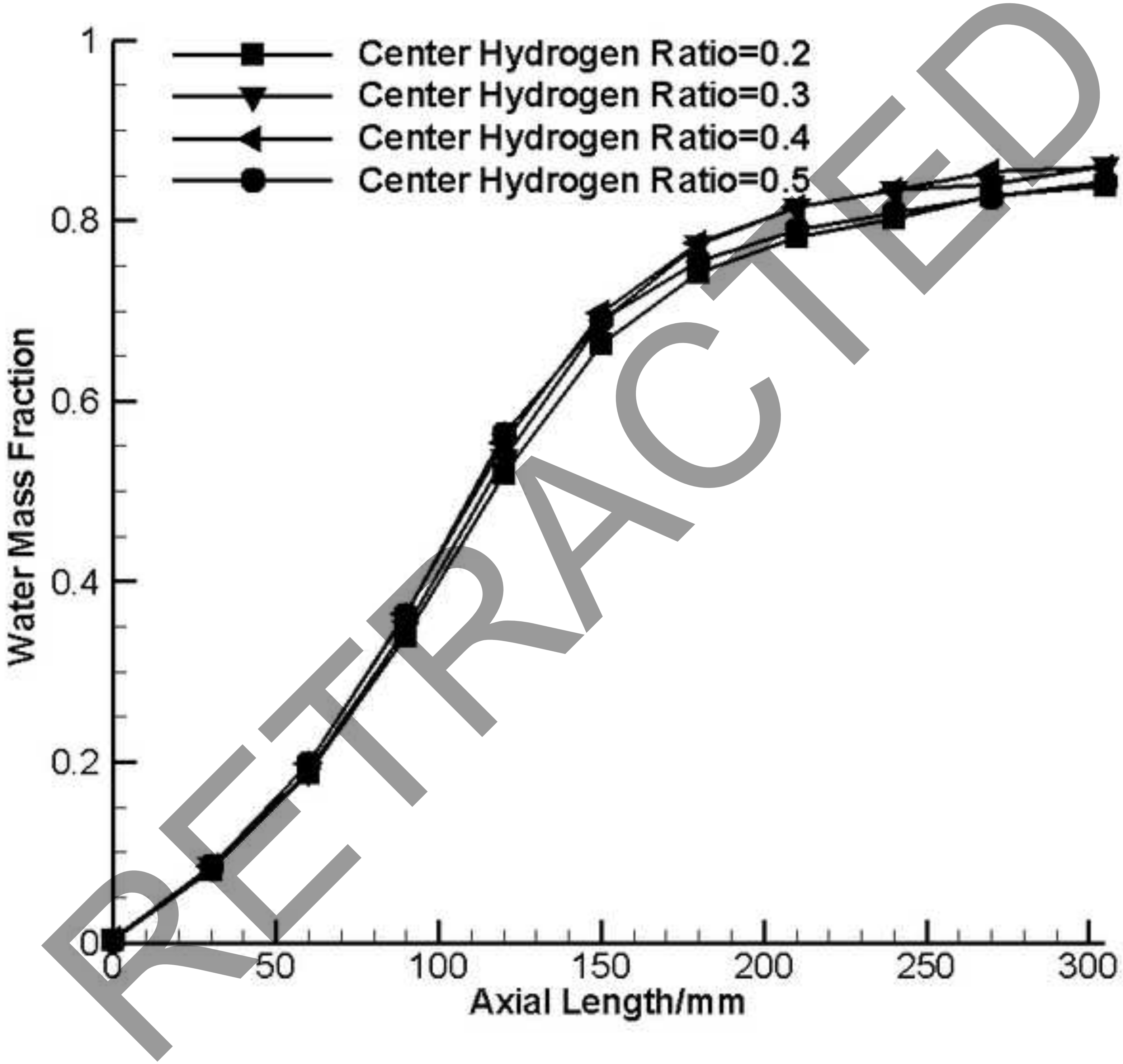
Figure


Temperature: 100 700 1300 1900 2500 3100 3700
Center hydrogen mass flowrate ratio 0.2
Center hydrogen mass flowrate ratio 0.3
Center hydrogen mass flowrate ratio 0.4
Center hydrogen mass flowrate ratio 0.5
0 50 100 150 200 250 300
Axial Length /mm

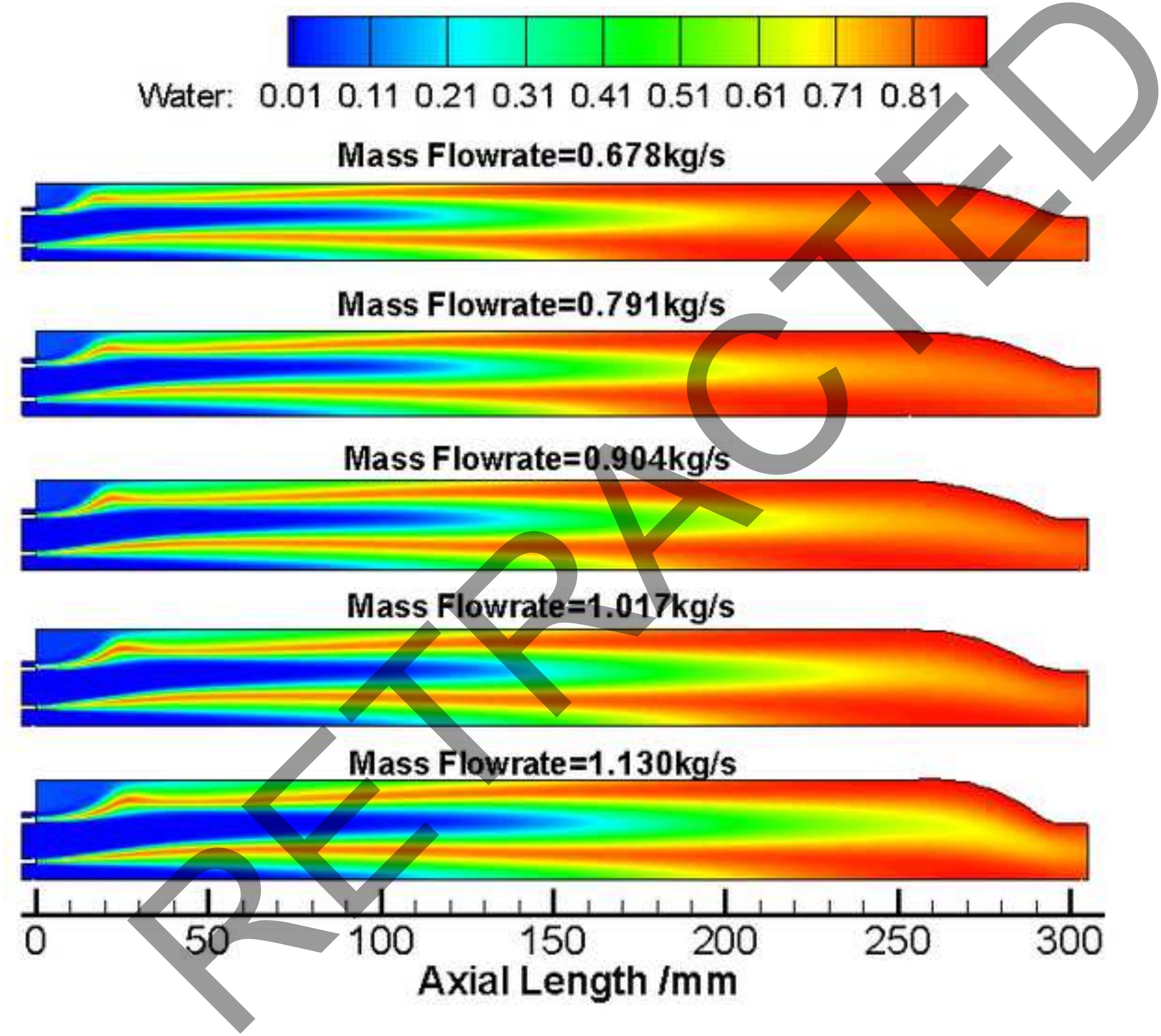
Figure


OH: 0.002 0.022 0.042 0.062 0.082 0.102 0.122
Center Hydrogen Mass Fraction=0.2
Center Hydrogen Mass Fraction=0.3
Center Hydrogen Mass Fraction=0.4
Center Hydrogen Mass Fraction=0.5
0
50
100
150
200
250
300
Axial Length /mm
RETRACTED

Figure

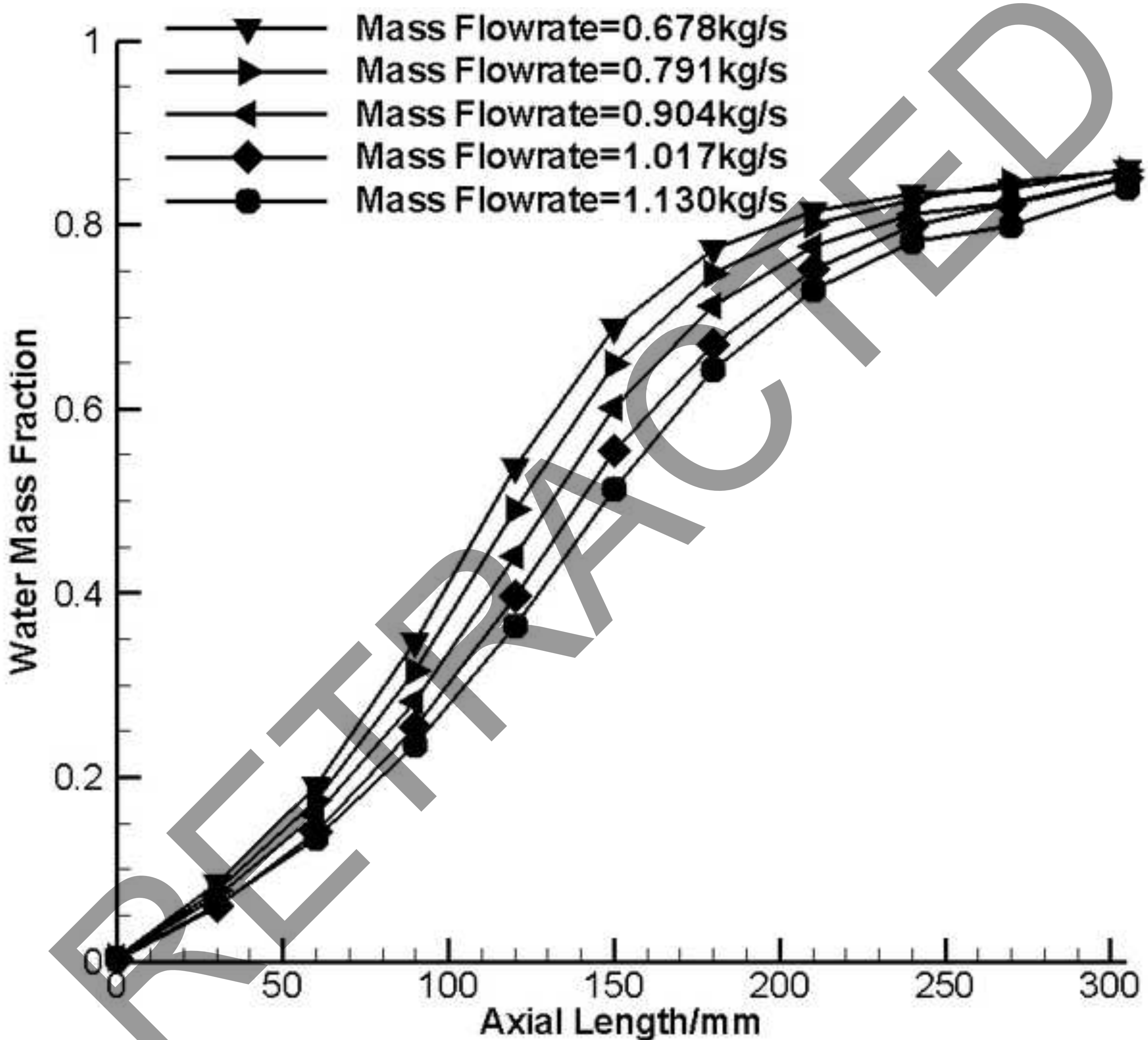

Center Hydrogen Ratio=0.2
Center Hydrogen Ratio=0.3
Center Hydrogen Ratio=0.4
Center Hydrogen Ratio=0.5
Water Mass Fraction
Axial Length/mm
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
RETRACTED

Figure



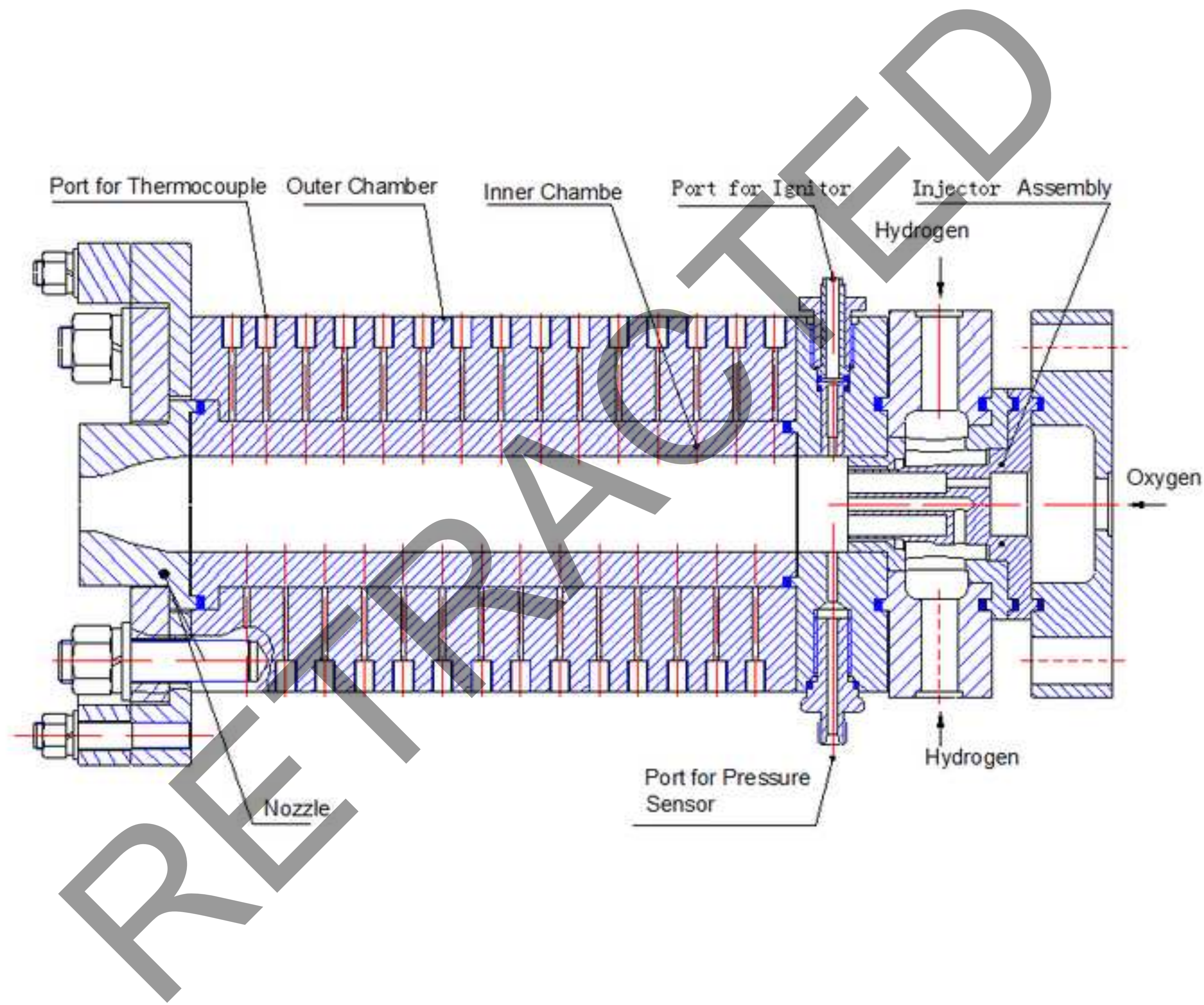
Water: 0.01 0.11 0.21 0.31 0.41 0.51 0.61 0.71 0.81
Mass Flowrate=0.678kg/s
Mass Flowrate=0.791kg/s
Mass Flowrate=0.904kg/s
Mass Flowrate=1.017kg/s
Mass Flowrate=1.130kg/s
0
50
100
150
200
250
300
Axial Length /mm
RETRACTED

Figure



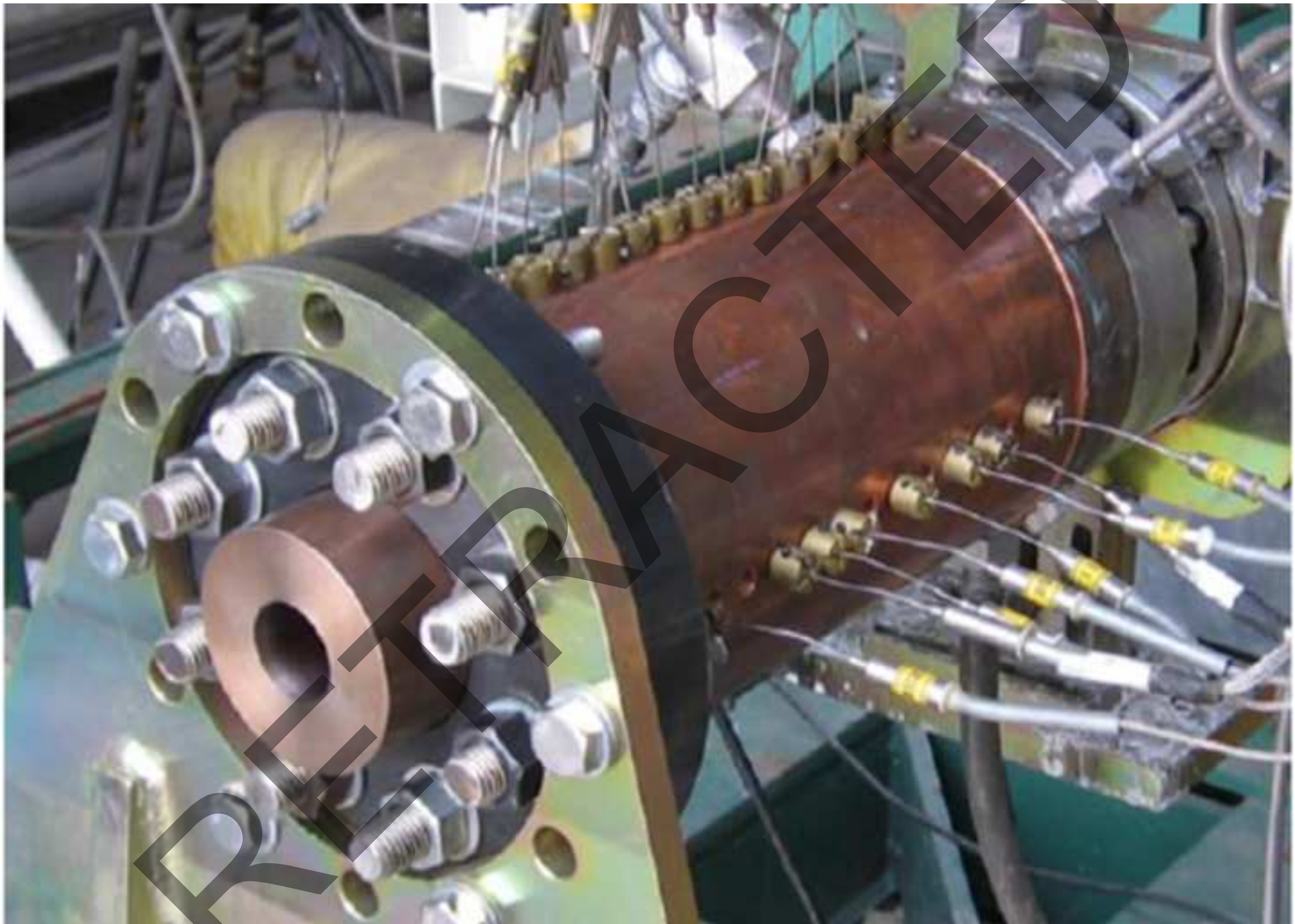
Mass Flowrate=0.678kg/s
Mass Flowrate=0.791kg/s
Mass Flowrate=0.904kg/s
Mass Flowrate=1.017kg/s
Mass Flowrate=1.130kg/s
Water Mass Fraction
Axial Length/mm
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300

Figure



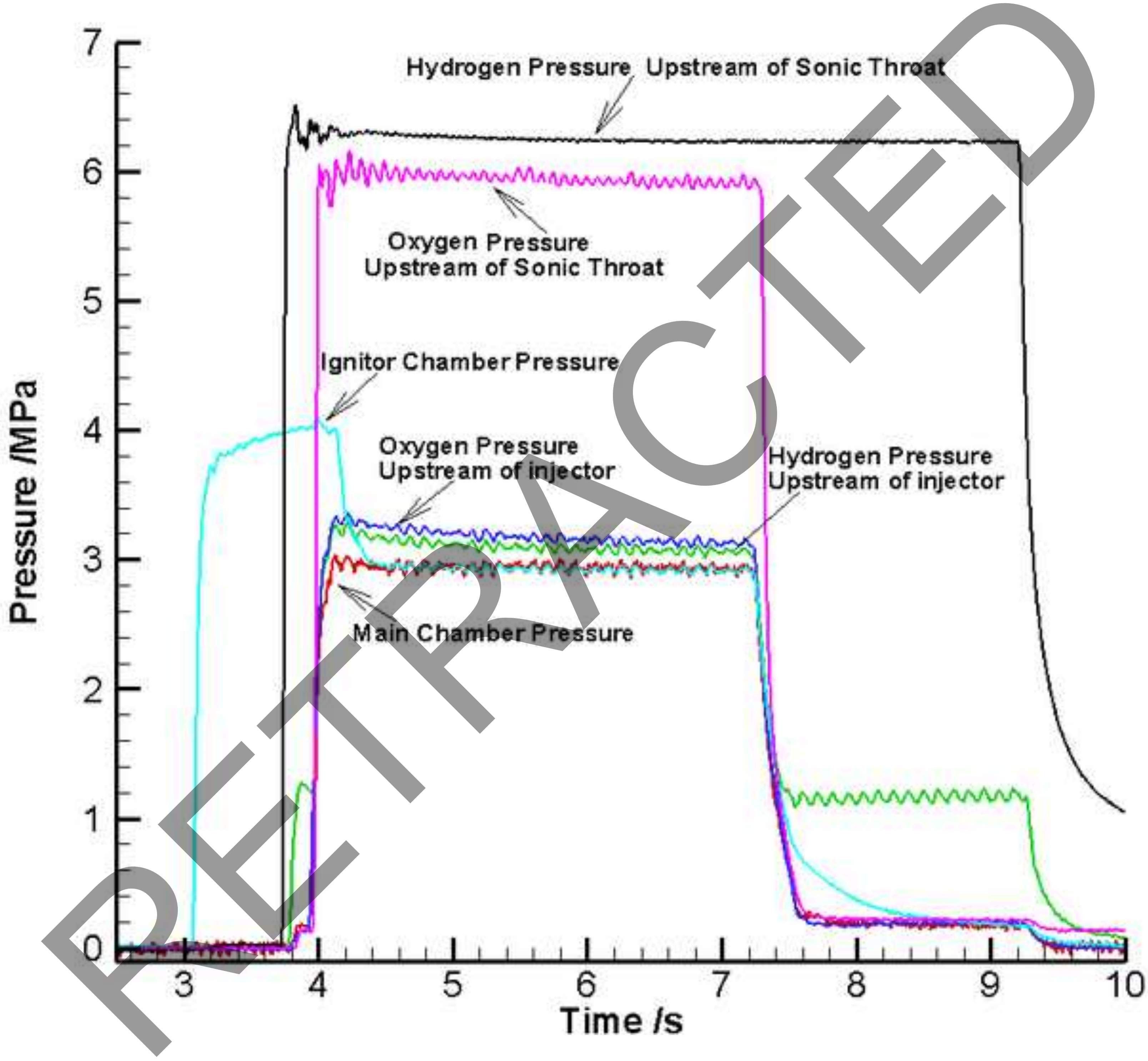
Port for Thermocouple
Outer Chamber
Inner Chambe
Port for Ignitor
Injector Assembly
Hydrogen
Oxygen
Hydrogen
Port for Pressure
Sensor
Nozzle
RETRACTED

Figure



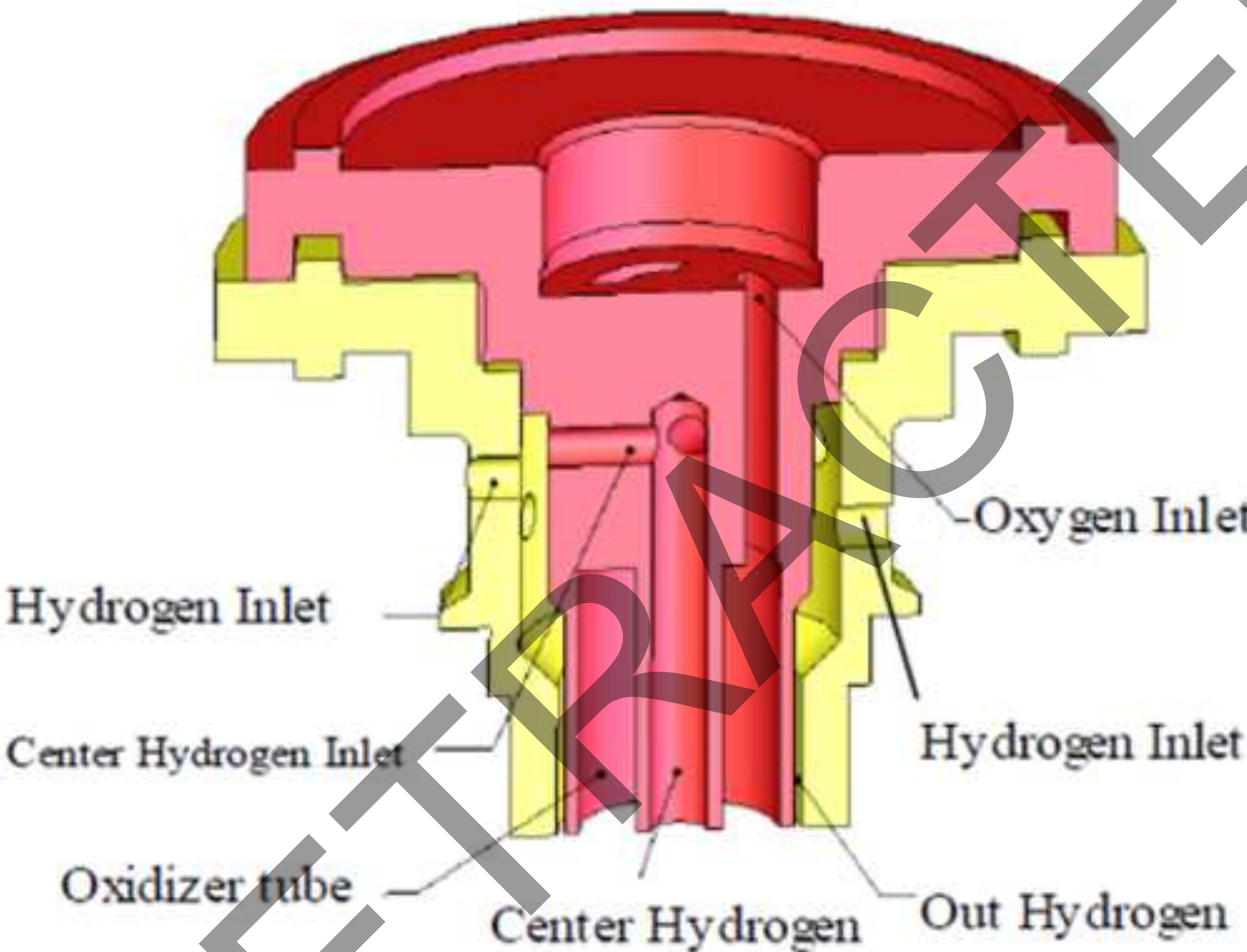
Figure

Figure



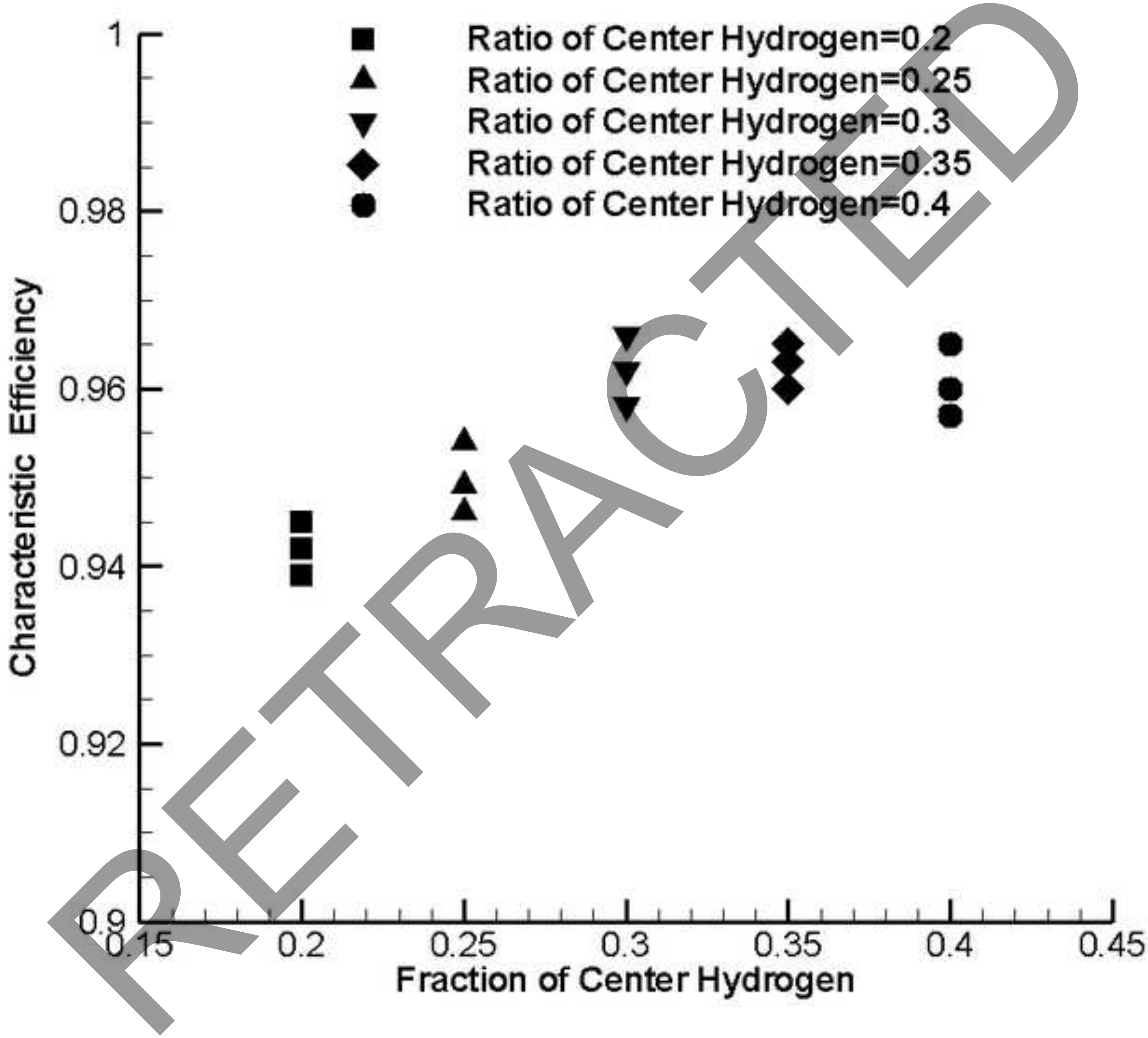
Hydrogen Pressure Upstream of Sonic Throat
Oxygen Pressure
Upstream of Sonic Throat
Ignitor Chamber Pressure
Oxygen Pressure
Upstream of injector
Hydrogen Pressure
Upstream of injector
Main Chamber Pressure
Pressure /MPa
Time /s
0
1
2
3
4
5
6
7
3
4
5
6
7
8
9
10
RETRACTED

Figure

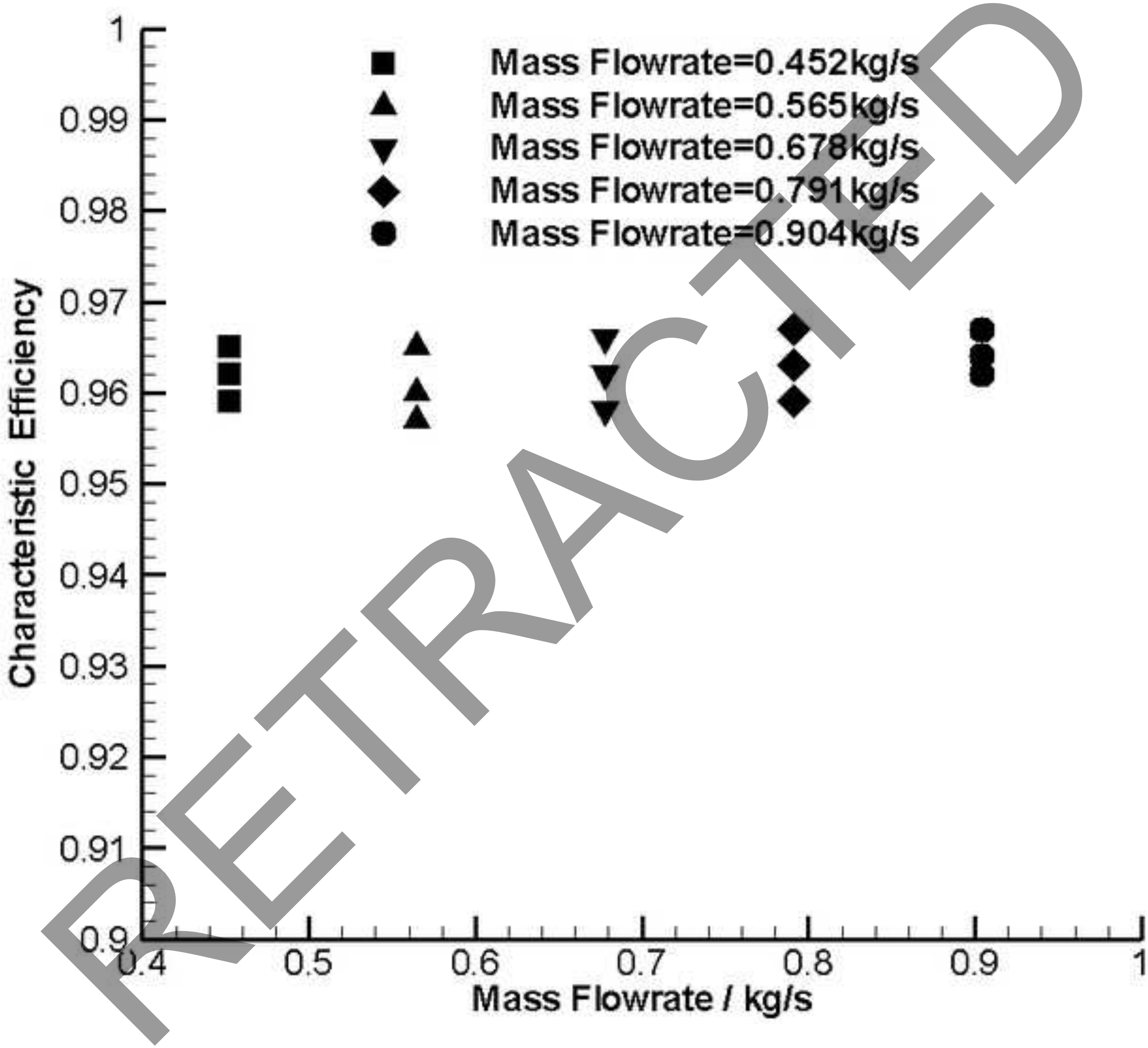


Oxygen Inlet
Hydrogen Inlet
Center Hydrogen Inlet
Hydrogen Inlet
Oxidizer tube
Center Hydrogen
Out Hydrogen

Figure


Ratio of Center Hydrogen=0.2
Ratio of Center Hydrogen=0.25
Ratio of Center Hydrogen=0.3
Ratio of Center Hydrogen=0.35
Ratio of Center Hydrogen=0.4
Characteristic Efficiency
1
0.98
0.96
0.94
0.92
0.9
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Fraction of Center Hydrogen
RETRACTED

Figure



Mass Flowrate=0.452kg/s
Mass Flowrate=0.565kg/s
Mass Flowrate=0.678kg/s
Mass Flowrate=0.791kg/s
Mass Flowrate=0.904kg/s
Characteristic Efficiency
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.9
0.4
0.5
0.6
0.7
0.8
0.9
1
Mass Flowrate / kg/s
RETRACTED