FLAMMABLE MIXTURE FORMATION AND MIXING RATES OF TRANSIENT GASEOUS FUEL JET WITH AIR IN TUMBLING OR SWIRLING MOTION

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Abstract

In this study the effects of angular momentum (barrel and axial swirl) on flammable mixture formation and mixing rate between chamber air and transient gaseous jets of hydrogen and methane were numerically investigated in several geometric configurations; in fixed volume cubic and cylindrical chambers, and in a variable volume cylindrical chamber with moving piston. The magnitude of the momentum, injection duration, and injection velocity are the main parameters whose effects were investigated. In the cylindrical chamber with mowing piston dissipation of a bulk air motion vortex, and the angular momentum decay during compression were also studied The numerical simulations were carried out with the use of KIVA3V code modified for gaseous injection with a standard k-ε model for turbulence.

It was found that hydrogen jet and air mixing under application of angular momentum lead to fast formation of flammable mixture, with the mixing rates several times larger than those for methane jet. Also dynamics of the hydrogen mixing as illustrated by the mixing rate curves is markedly different from those for methane with the same magnitude of angular momentum. The mixing rate curves for hydrogen feature one strong local maximum at time which is half or less of the hydrogen jet injection duration time. Mixing of methane jet with air at all conditions resembles that of hydrogen jet mixing with air at zero or lower levels of angular momentum.

Keywords: *Mixing, axial swirl, barrel swirl (tumble), numerical modelling, KIVA.*

1. Introduction

The performance, efficiency and exhaust emissions of power generating devices that use mixtures of fuel and air such as internal combustion engines, gas turbines, and furnaces are highly dependent on air-fuel mixing process outside or inside of combustion chamber. Therefore, to increase the performance efficiency and reduce the pollutant emissions, the adequate air-fuel mixture preparation becomes essential in effective design of combustion chamber. Increasing turbulence level of fluid inside the chamber is one standard way to enhance air-fuel mixing. Accordingly, it was demonstrated [1-3] that a better understanding of the turbulent flow structure inside the chamber is essential for a better design and performance of combustion devices. In this study the effects of two coherent bulk motions in chamber air, namely a barrel swirl (tumble) and axial swirl, and their interaction with transient gaseous fuel jet are studied with the use of KIVA3V numerical code [4, 5].

2. Computational model

Hydrogen and methane jet injections have been chosen to represent transient gaseous fuel jets. Hydrogen has wide flammability limits, small ignition energy, and fast propagating flame. While methane with its lower flame temperature, simple chemical structure (i.e. inherent high hydrogen to carbon ratio) offers a potential for nitrogen oxide NO_x reduction.

Cubic and cylindrical chambers, shown in Fig. 1, with the same volume of 1L, are considered as computational domains into which geous fuels are injected. The injection is from the top wall down. A group of 4 by 4 cells located on the top wall are set to represent the injector and approximately 64000 cells are used to mesh both geometries. Initially, the chambers contain air at standard temperature and pressure (T = 293K and P = 1atm) with prescribed values for turbulent kinetic energy and length scale of 0.1 cm^2/s^2 and 0.1 cm, respectively. In Tab. 1, a simulation matrix is shown for different conditions at which two fuels are injected. The injection duration was selected to ensure that the total equivalence ratio is $\phi = 0.76$.

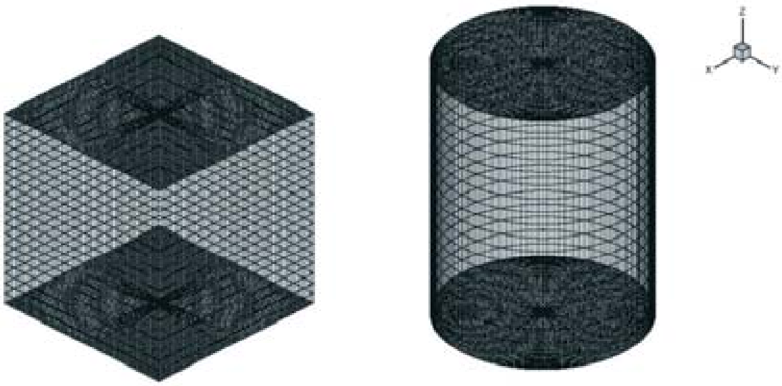

Fig. 1 Computational domains: cubic chamber 10×10×10 cm^3, and cylindrical chamber D = 10 cm; h = 12.7 cm, both chambers have the same volume of 1L.

The rotational motion of the chamber air is determined by the initial velocity profile inside the chambers. The velocity profiles are chosen to be the Bessel functions and are set to provide an amount of angular momentum that corresponds to an arbitrary rotational air speed of 2000rpm. That introduces 1.44e5 kg/s of angular momentum for an axial swirl in cylindrical and cubic chambers and for a barrel swirl in the cubic chamber. In the cylindrical chamber the barrel swirl (tumble) brings in 3.79e5 kg/s of angular momentum. For easy comparison, the results are presented as functions of the arbitrary axial swirl ratio (ASR) and tumble ratio (ATR) which result from normalization of the actual angular momentum by the reference value at 2000 rpm (for which the ATR and ASR are both 1).

Tab. 1 Simulation matrix

	V_{inj} (m/s)	t_{inj} (ms)	Chamber geometry	Swirl direction
CH_4	150	10	cubic	axial
			cylindrical	axial
			cubic	barrel
			cylindrical	barrel
H_2	150	20	cubic	axial
			cylindrical	axial
			cubic	barrel
			cylindrical	barrel

From experimental observation, modellers have determined that the Bessel function profile more accurately represents the rotational flow within enclosure. Fig. 2 illustrates the Bessel function velocity profile provided in KIVA [4, 5] and compares it with the „wheel" type flow for the same swirl number. The quantity α is a dimensionless constant that defines the initial angular velocity profile and lies between 0.0 (the wheel type flow limit) and 3.83 (zero velocity at the wall). A value suggested by Wahiduzzaman and Ferguson [6] for typical engine applications is about 3.11. In this study, the Bessel function profile is chosen to give the same angular momentum value (as listed above) of the wheel flow with the same swirl number. Thus the initial slope of the velocity curve, $\alpha = 3.11$ is necessarily higher than the corresponding slope for the wheel flow.

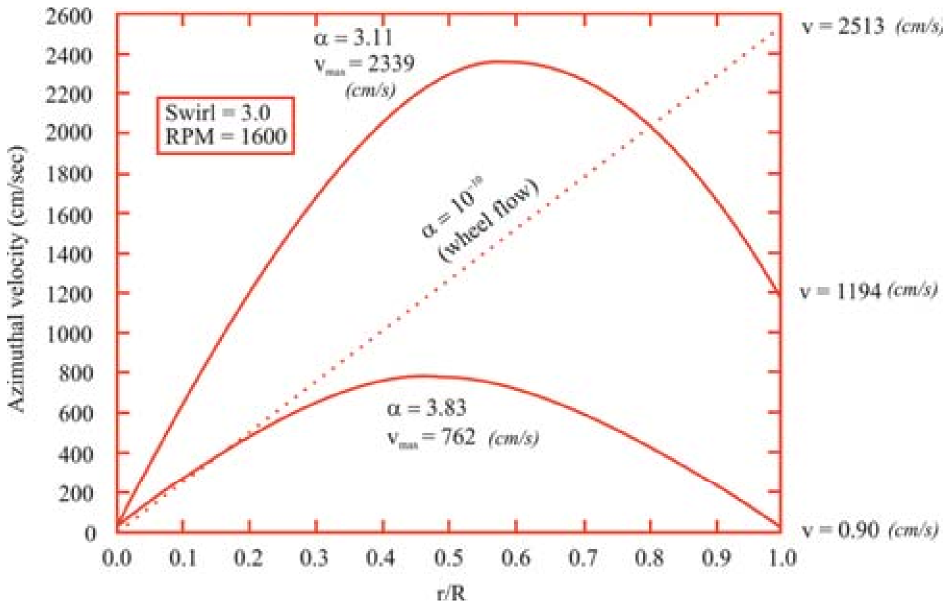

Fig. 2. Besse l - function swirl velocity profile provided in KIVA setup.

3. Results

Time history of flammable mixture formation for two geometries and for both fuels is shown in Fig. 3. In the figure volume of flammable mixture over time is depicted at two levels of the barrel swirl (zero and maximum investigated). In Fig. 4 similar results for the axial swirl are shown. At zero levels of both the barrel and axial swirl and for all conditions the formation of flammable mixture proceeds very slowly. Also the fuel type does not make much difference at these conditions. Even for hydrogen, after 70 ms only 85% of the chambers volume is occupied by the flammable mixture. For hydrogen the substantial increase in the volume of flammable mixture occurs with addition of the angular momentum (at ART = ASR = 2.5) in both geometries and both swirl directions. For methane the increase in the volume of flammable mixture is noticed only in the cylindrical chamber and for the axial swirl (right frame in Fig. 4, at ASR = 2.5).

More information about dynamics of mixing is revealed in Fig. 5 and 6 where mixing rate over time is plotted. The mixing rates of hydrogen are two times higher of those for methane for all conditions. The largest mixing rate for hydrogen is noted in the cubic chamber and for the barrel swirl (Fig. 5, left frame), however mixing process at this rate does not last for long. It is characteristic that for all conditions studied the mixing rate curves for hydrogen feature one strong local maximum at time which is half or less of the hydrogen jet injection duration time (20 ms). The more moderate but sustained for longer time are mixing rates observed in the cylindrical chamber with the axial swirl (Fig. 6, right frame). Consequently this result in the shortest mixing time of 27 ms (solid curve in Fig. 4, right frame) for the hydrogen jet. At the same conditions for methane only 83% of volume is occupied by the flammable mixture and another 15ms is needed bring this number to 93%.

In Fig. 7 volume of flammable mixture versus time for the methane injection (Fig. 7, left frame), and the hydrogen injection (Fig. 7, right frame) for the gradually increasing level of barrel swirl (tumbling motion) is shown. Results indicate that there is an optimal level of barrel swirl beyond which no substantial gains in the volume of flammable mixture are achieved. It is also interesting to note that this optimal level of the barrel swirl for hydrogen is higher by factor of two.

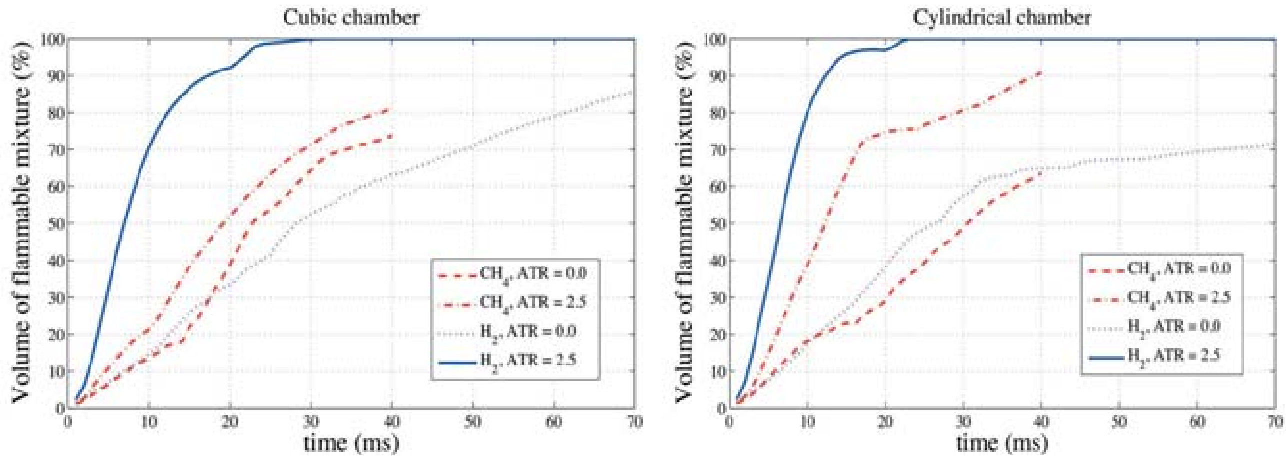

Fig. 3. Volume of flammable mixture at different levels of the barrel swirl for H_2 and CH_4; in cubic chamber (left frame), and in cylindrical chamber (right frame).

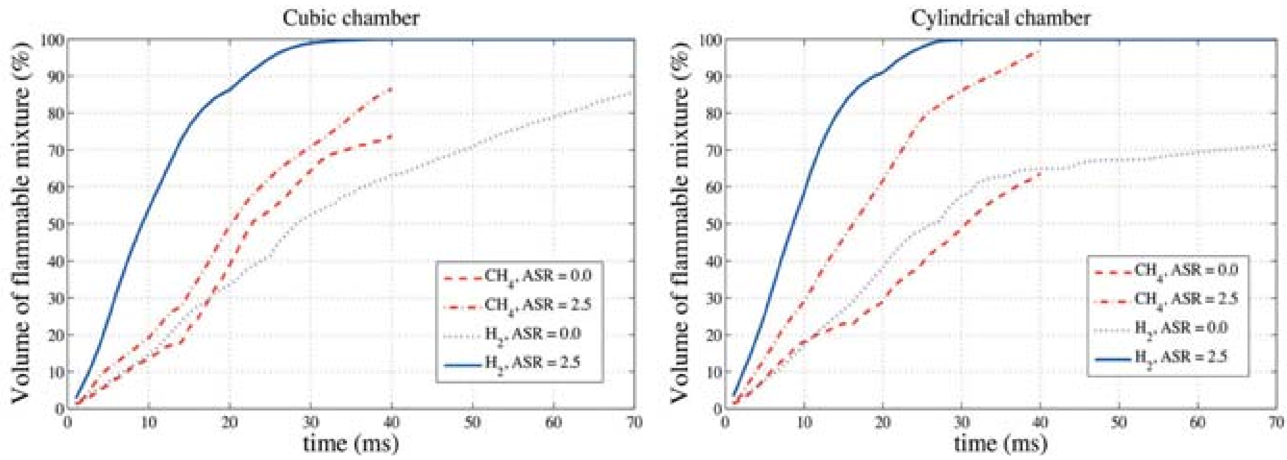

Fig. 4. Volume of flammable mixture at different levels of the axial swirl for H_2 and CH_4; in cubic chamber (left frame), and in cylindrical chamber (right frame).

More results on the volume of flammable mixture versus time at increasing levels of swirl are shown in Fig. 8 - 10. It is characteristic that the mixing of the methane jet in the cubic chamber is only little sensitive to the level of the swirl (and it does not matter if barrel swirl or axial swirl) (left frames in Fig. 7-8). Furthermore, over time the mixing process does not change much when the level of swirl is increased. In the cylindrical chamber, the mixing of methane jet responds to the level of the swirl, and for the largest level of the swirl 2.5, it is the axial swirl which more effective (left frames in Fig. 9 and 10). For the hydrogen jet, the chamber geometry does not seem to make a difference. The hydrogen injection is sensitive to the type of swirl; and is the barrel swirl (tumbling) that is more effective.

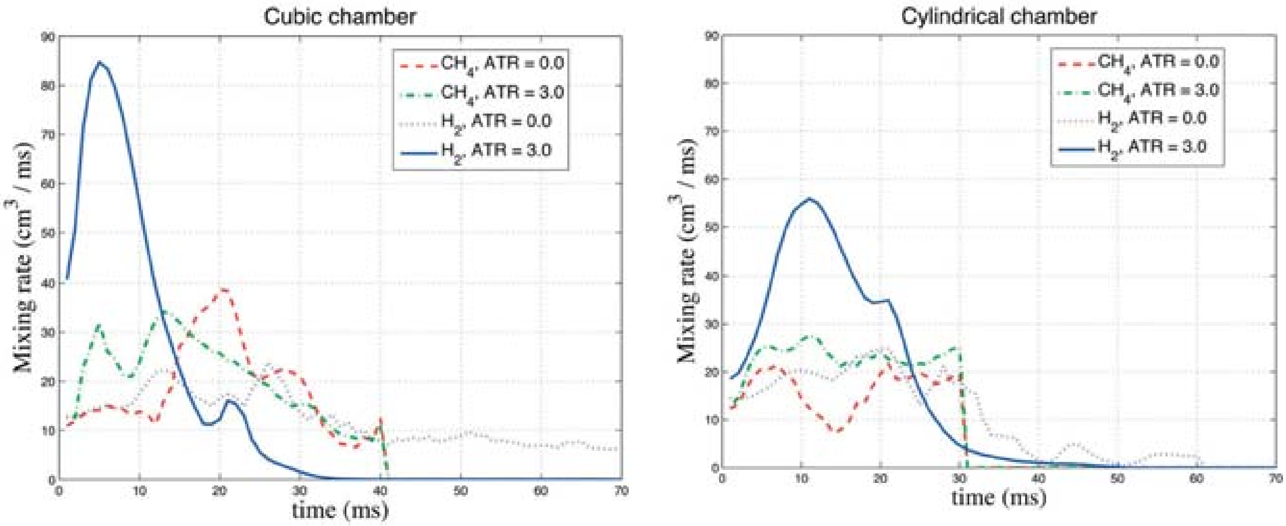

Fig. 5 Mixing rate at different levels of the barrel swirl for H_2 and CH_4; in cubic chamber (left frame), and in cylindrical chamber (right frame)

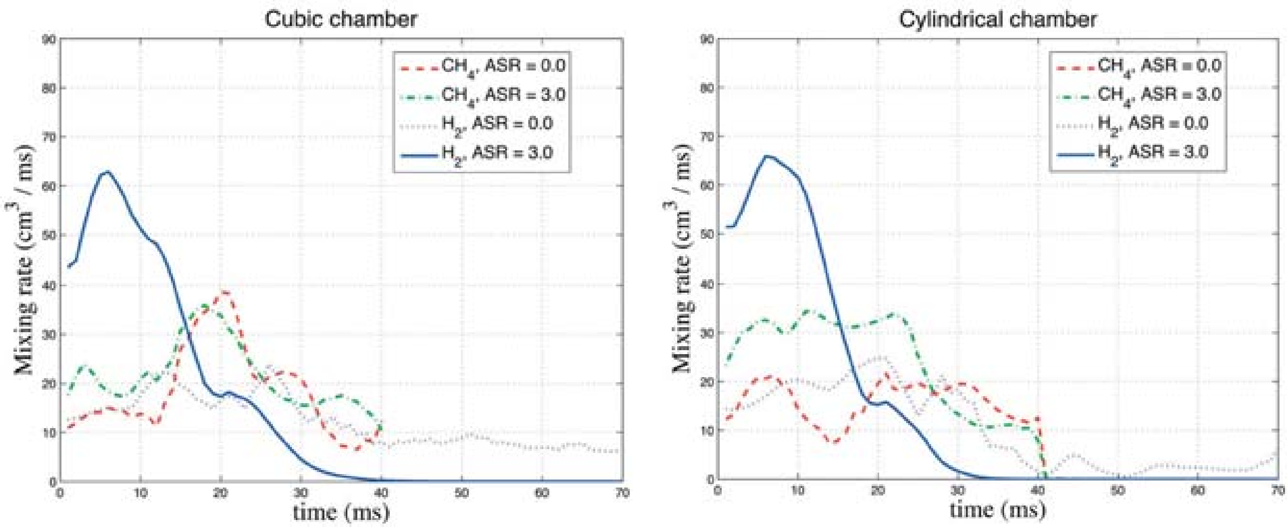

Fig. 6 Mixing rate at different levels of the axial swirl for H_2 and CH_4; in cubic chamber (left frame), and in cylindrical chamber (right frame)

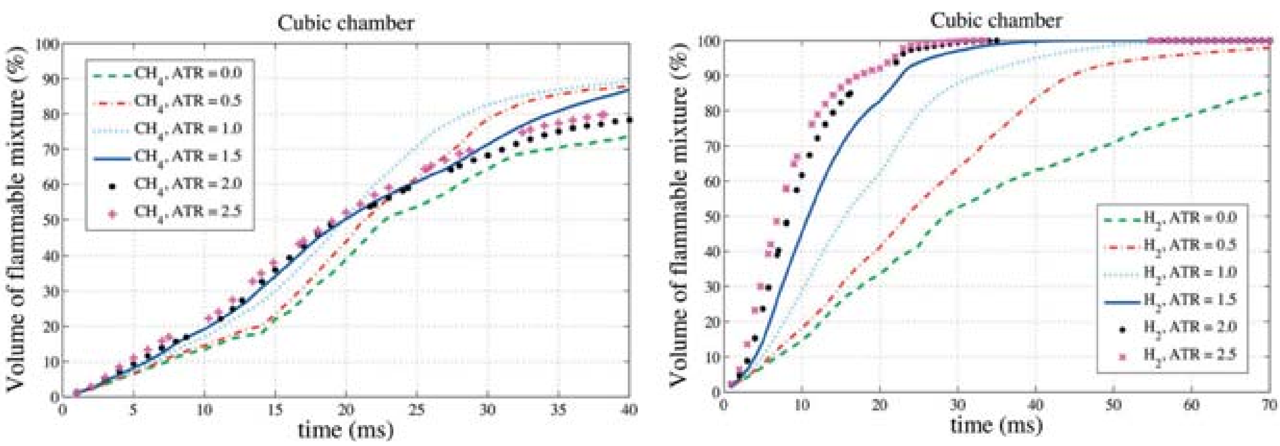

Fig. 7 Volume flammable mixture at different levels of the barrel swirl in a cubic chamber; for methane (left frame), and for hydrogen (right frame)

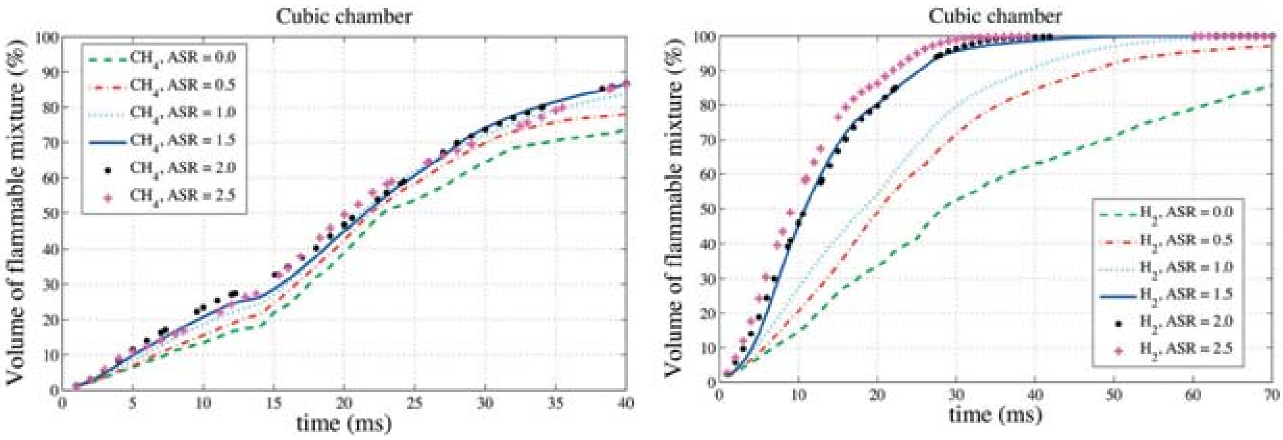

Fig. 8. Volume flammable mixture at different levels of the axial swirl in a cubic chamber; for methane (left frame), and for hydrogen (right frame)

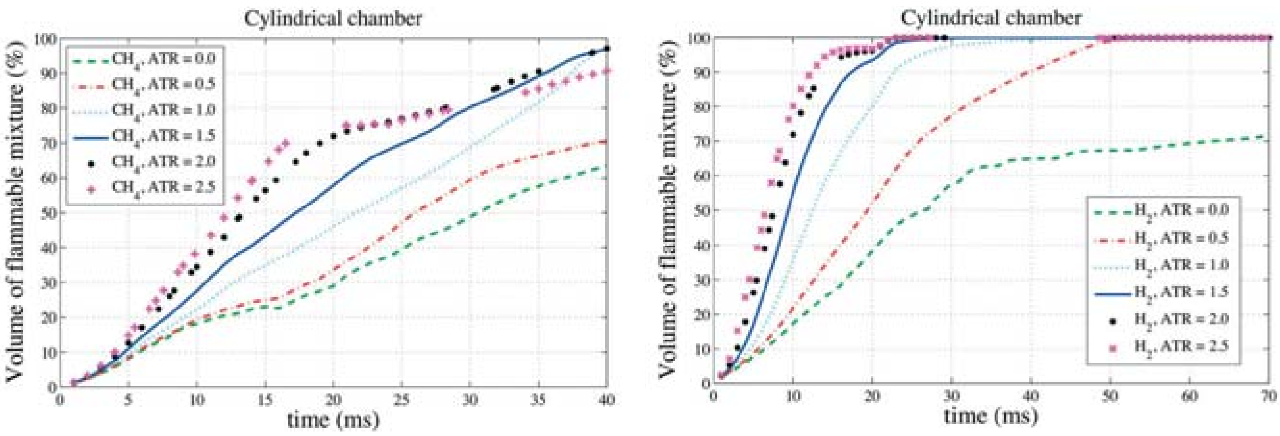

Fig. 9. Volume flammable mixture at different levels of the barrel swirl in a cylindrical chamber; for methane (left frame), and for hydrogen (right frame)

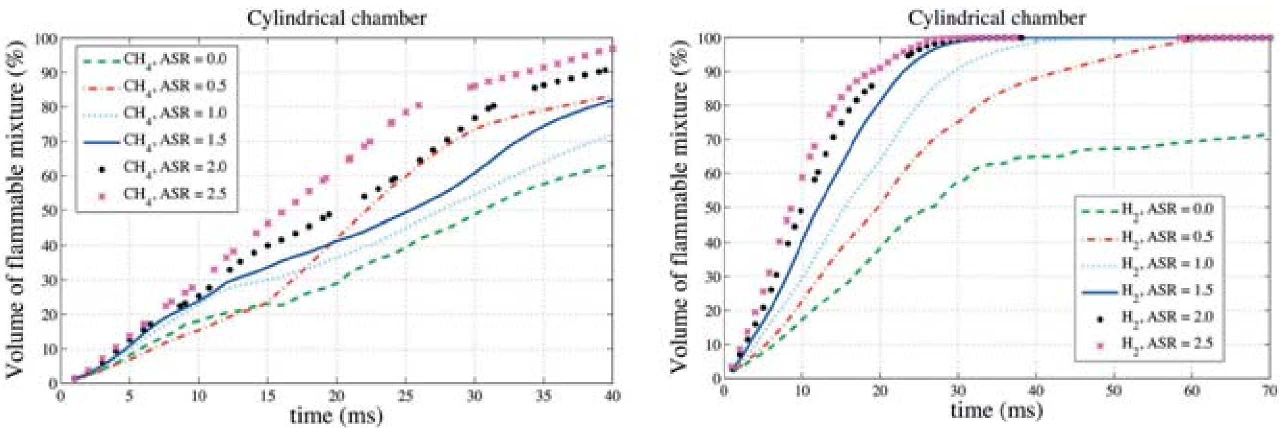

Fig. 10 Volume flammable mixture at different levels of the axial swirl in a cylindrical chamber; for methane (left frame), and for hydrogen (right frame)

4. Conclusions

In this study the effects of angular momentum (barrel and axial swirl) on flammable mixture formation between chamber air and transient gaseous jets of hydrogen and methane in cubic and cylindrical chambers were numerically investigated. The magnitude and the orientation of the momentum were the main parameters. It was found that the hydrogen jet and air mixing result in fastest formation of flammable mixture, with the mixing rates several times larger than those for the methane jet. The mixture formation process for the hydrogen injection was little sensitive to the chamber geometry, and it was more effective with the application of the barrel swirl (tumble). Also dynamic of the hydrogen mixing is markedly different from those for methane with the same magnitude of angular momentum. Mixing of the methane jet with air under all conditions resembles that of the hydrogen jet mixing with air at zero or lower levels of the angular momentum. The mixing of the methane jet in the cubic chamber is only little sensitive to the level of the swirl regardless the swirl orientation. Furthermore, over time the mixing process of the methane jet does not change much when the level of swirl is increased. In the cylindrical chamber, the mixing of methane jet responds to the level of the swirl, and it is the axial swirl which more effective.

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