A comprehensive study on the design and computational analysis of an air swirl burner

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Abstract. This paper presents a comprehensive study on optimizing the design of a vane-type air swirl burner, along with a computational analysis comparing the combustion of diesel and hydrogen fuel within the same burner. For the combustion simulations, a coupled approach was employed involving a Lagrangian approach with the Discrete Phase Model to track the trajectories of fuel particles providing a comprehensive understanding of the particulate dynamics within the system. This research aimed to analyze hydrogen's potential as a sustainable energy carrier in comparison to its conventional counterparts such as diesel fuel. The results showed that the contours of hydrogen fuel revealed a well-defined and intense flame front whereas it was not the same in the case of diesel fuel which had a less intense flame front.

1 Introduction

The critical need for energy-efficient and environmentally conscious combustion technologies have gained prominence amidst the global challenges surrounding traditional energy sources. As the environmental impact of these conventional resources undergoes scrutiny, there is a growing urgency to explore cleaner and more sustainable alternatives. In direct response to this imperative, the current research is carried out, focusing on the design and computational analysis of a vane-type air swirl burner with a fixed swirl number. The vane-type air swirl burner is a technology designed to enhance the combustion process by utilising its vanes to provide a swirling flow to create a well-defined and stable flame pattern. Swirling flows are commonly found in most practical applications, such as gas turbine combustors, furnaces, spraying machines, whirlpools, cyclone separators, and vortex shedding from aircraft wings [1,2]. The swirl intensity for rotating flows is usually characterized by the non-dimensional swirl number $S = G_\theta,/G_z R$, which represents the ratio of the axial flux of angular momentum, G_θ to the axial flux of axial momentum, G_z times the nozzle radius [3]. In this study, a Lagrangian approach coupled with the Discrete Phase Model (DPM) was employed to investigate the dynamic behaviour of particles within a fluid medium, specifically focusing on the use of liquid hydrogen as fuel [4]. The Lagrangian approach is chosen for its ability to track individual particles throughout their trajectories [5]. It provides a detailed insight into the complex interactions and motions of discrete entities

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within the liquid hydrogen flow. By adopting the Lagrangian perspective a better understanding of how particles respond to local flow conditions and navigate through intricate fluid structures was developed which is particularly relevant in the case of liquid hydrogen fuel. The integration of the Discrete Phase Model is used to simulate and analyze the movement of distinct particles, aiding in modelling the discrete nature of the dispersed phase in the liquid hydrogen environment [6]. This combined Lagrangian-DPM framework was chosen to address the specific research questions related to individual particle dynamics and interactions in the context of liquid hydrogen as a fuel, aligning with the intricate nature of the studied phenomena in this unique fuel setting.

There are numerous studies available in the literature that discuss the swirling flow, hydrogen combustion and the Discrete Phase Model. One such study examined isothermal free swirling jets for five different swirl numbers at a fixed Reynolds number [1] Later on the results were further evaluated for local entrainment rate in the initial region of isothermal free swirling jets by Stereo PIV and for coherent structures in the near-field region of an isothermal free swirling jet after vortex breakdown [3,7]. Another study explored the use of hydrogen-containing fuel blends to determine their flashback and blow-off limits in swirl burners using the Lewis and von Elbe critical boundary velocity gradient expressions [8]. The authors of another study examined the effect of hydrogen addition on the combustion behaviours of turbulent unconfined swirling flames. This study used the steady laminar flamelet combustion and the realizable k-Ɛ turbulence models to model the behaviour [9]. Based on the results, the amount of hydrogen in the fuel significantly affects the flame structure. Another study modelled a natural gas diffusion flame, taking into account the effect of the swirl number [10]. It is reported that combustion characteristics change significantly depending on changes in swirl number. A numerical study related to the CH4-H2 mixtures was also conducted, and the results showed that hydrogen addition leads to an increase in flame temperature [11]. An experimental study was conducted on hydrogen-methane blended fuels, and according to measurements, hydrogen-methane blended fuels can be used successfully without any changes to conventional natural gas burners [12]. One study explored the effects of swirl number on the combustion characteristics of hydrogen Another study conducted both experimental and numerical studies of gaseous fuel combustion in a swirl chamber [13]. A study was conducted to discuss the use of the discrete phase model in fluid flow [6]. Authors of another study were verified the discrete phase model with water particle flow in a tundish [5].

Although there are some studies about with and without swirling combustion processes, these studies are generally related to methane or natural gas flames. Investigations related to the combustion of hydrogen-containing fuels in swirl combustors are very restricted in the literature. Therefore, this study focuses on the combustion processes and properties of hydrogen fuel and compares those with the ones of diesel fuel with fixed swirl numbers.

2 Simulation setup

2.1 Apparatus

A vertically oriented vane-type swirl burner was designed with the height of 500 mm and the diameter of 100 mm and is used to carry out the combustion processes of hydrogen and diesel fuel. The fuel is injected through a fuel inlet which has a diameter of 10 mm. The swirl generator is of tangential entry type to promote a strong and controlled swirl, which is beneficial for achieving better mixing of fuel and air, as well as enhancing flame stabilization. The tangential air is introduced through 10 tangential inlets to impart angular momentum upstream from the base of the burner. As a vane-type swirl burner, it is equipped with a system of vanes, where the total number of vanes is 10, each having a length of 50 mm, a width of 4 mm, a height of 26 mm and a vane angle of 139.48 degrees.

2.2 Simulation properties

The software which has been used for the simulation is the Ansys Fluent 2023 R2 Student Version. The solver employed was of the pressure-based type along with the k-omega type of viscosity model. A coupled approach involving the Discrete Phase Model and the Non-Premixed Combustion Model was employed with the Probability Density Function. In the Discrete Phase Model simulation, the particle treatment involves unsteady particle tracking with a particle time step size of 0.0001 seconds over a single time step. The tracking parameters are configured with a maximum number of steps set at 10000 and a length scale of 0.0001 meters. The injection properties specify the use of droplets with a pressure-swirl atomizer, employing 100 particle streams. The injector is positioned 0.04m above the zero point. The point properties for the injected droplets include an initial temperature of 300K, a flow rate of 0.003 kg/s, and a simulation period from 0 to 20 seconds. The injector's inner diameter is 0.001 meters, and the spray is emitted with a half angle of 15 degrees. The total number of iterations is set to 900, reflecting the iterative nature of the solution process employed to achieve convergence and obtain accurate results.

3 Methodology

The first phase of the methodology involved the process of designing Computer-Aided Design (CAD) models for the burner and the vanes using SolidWorks 2022. The dimensions of both components are provided in the Apparatus section (2.1). Utilizing design software, the CAD models serve as the foundational blueprints for the subsequent simulations, ensuring a precise representation of the physical burner within the virtual environment.

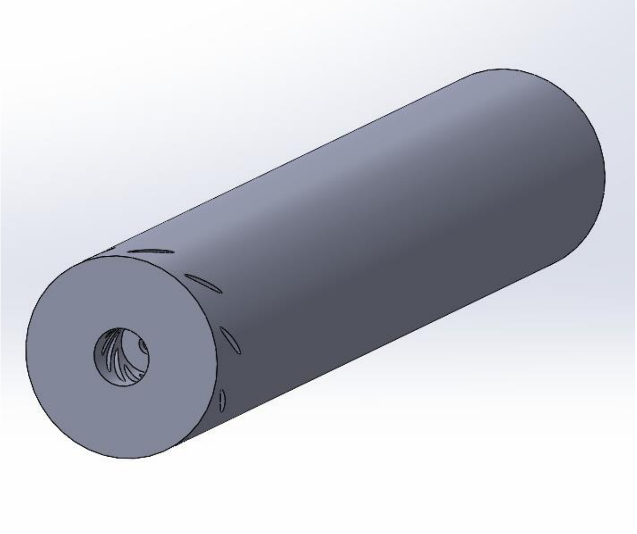

Fig. 1. CAD model of the vane-type air swirl burner

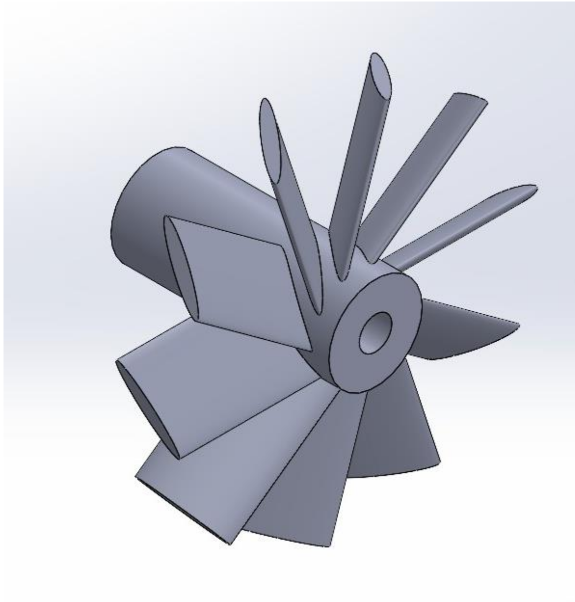

Fig. 2. CAD model of the vanes of the vane-type air swirl burner

Following the CAD design phase, the next step involves meshing the created models using Ansys. Meshing is a crucial process that discretizes the geometric structures into smaller, manageable elements, allowing for the accurate representation of fluid flow and combustion phenomena during simulations.

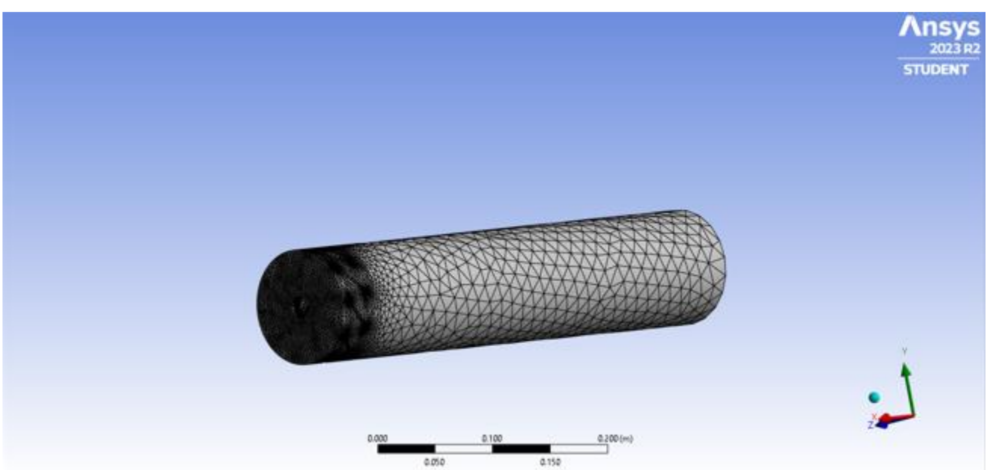

Fig. 3. Meshed model of the burner

Table 1. Properties of the mesh

Display Style	Use Geometry Setting
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	9.e-002 m (0.09 m)
Export Format	Standard
Export Preview Surface Mesh	No
Use Adaptive Sizing	No
Growth Rate	Default (1.2)
Max Size	Default (0.18)
Mesh Defeaturing	Yes
Defeature Size	Default (4.5e-004 m)
Capture Curvature	Yes
Curvature Min Size	Default (9.e-004m)
Curvature Normal Angle	Default (18.0 degrees)
Capture Proximity	No
Bounding Box Diagonal	0.51962 m
Average Surface Area	1.138e-002 m^2
Minimum Edge Length	3.1416e-002 m
Check Mesh Quality	Yes
Target Skewness	Default (0.9)
Smoothening	Medium
Mesh Metric	None
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Number of CPUs for Parallel Part Meshing	Program Controlled
Rigid Body Behaviour	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Default (8.1e-004)
Generate Pinch on Refresh	No
Nodes	57332
Elements	300692
Show Detailed Statistics	No

4 Results and discusssion

This section deals with the simulation results focusing on the combustion characteristics of hydrogen and diesel fuel within the vane-type air swirl burner. First, the flame stability and the energy release patterns of both fuels will be discussed with the help of the contours of the total temperature and pathlines (coloured by total temperature). Second, the results of the Discrete Phase Model will be presented through its scaled residual graphs.

4.1 Flame stability and energy release patterns

In the case of hydrogen combustion, the total temperature contours reveal a well-defined and intense flame front. The contours (Fig.5.) exhibit elevated temperatures concentrated in the core of the flame, which signifies effective combustion and substantial energy release. The intense heat in this region indicates that hydrogen, a highly reactive and clean-burning fuel, undergoes rapid combustion, resulting in a concentrated and high-temperature flame. This is a characteristic feature of hydrogen's combustion behaviour, known for its ability to produce high-temperature flames [13,14].

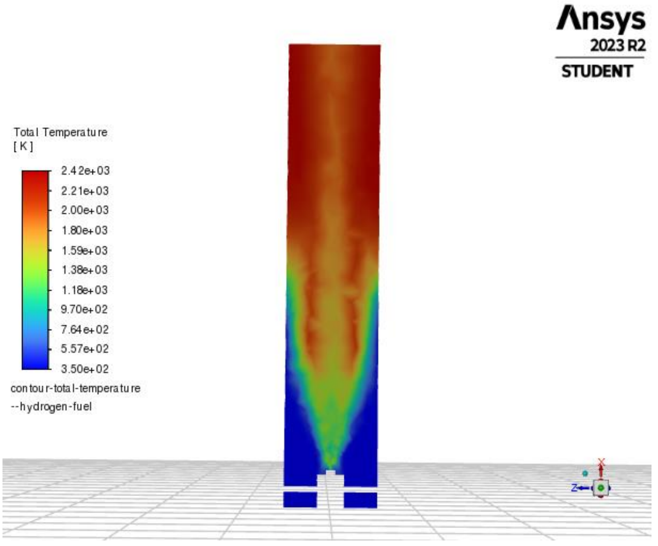

Fig. 5. Contour of Total Temperature (Hydrogen Fuel)

Contrasting the results for hydrogen, the total temperature contours (Fig.6.) for diesel fuel showcase a broader and less intense flame front. The contours depict variations in temperature across the combustion zone, reflecting the different combustion characteristics of diesel. Diesel combustion typically involves a more gradual and distributed release of energy compared to hydrogen. The broader flame front suggests a longer combustion duration and a more dispersed heat release pattern. This behaviour aligns with the characteristics of diesel combustion, where the ignition and combustion processes are influenced by factors such as fuel properties and air-fuel mixing [13,15].

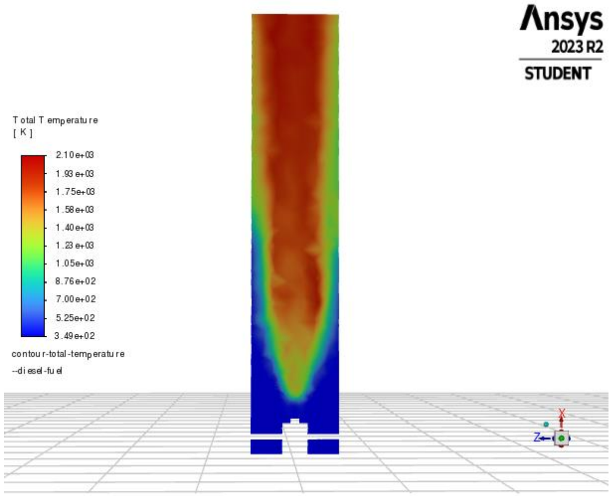

Fig. 6. Contour of Total Temperature (Diesel Fuel)

In the case of hydrogen combustion, the contours of pathline intensity coloured by total temperature reveal a dynamic and well-defined swirling motion within the Air Swirl Burner. The pathlines, colored to represent total temperature variations, showcase a concentrated and intense flame front characterized by high temperatures. The swirling motion contributes to efficient fuel-air mixing, promoting uniform combustion and elevating temperatures in the core of the flame. The result is a visually striking representation of the optimized combustion of hydrogen, with the pathlines vividly illustrating the heat release patterns and the spatial distribution of high-temperature regions. The intense and concentrated pathlines, colored by elevated total temperatures, underscore the effectiveness of hydrogen combustion within the Air Swirl Burner. The visualization reinforces the notion of hydrogen as a high-energy and clean burning fuel, with the pathlines highlighting the controlled and efficient combustion that contributes to the overall performance of the burner.

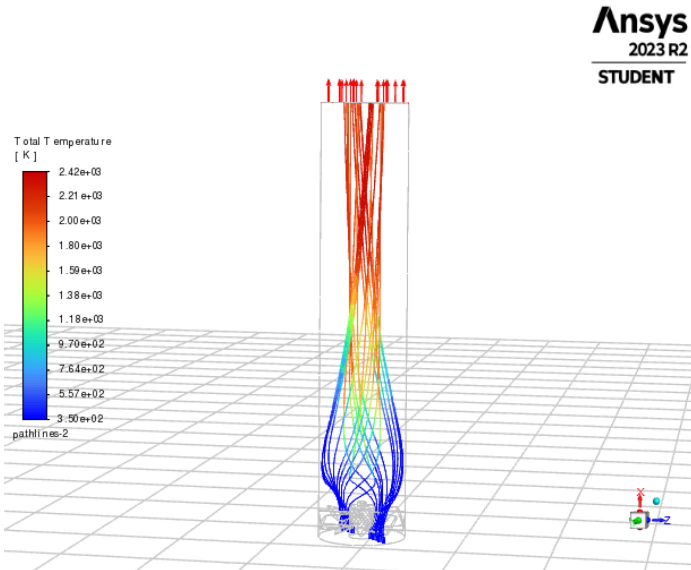

Fig. 7. Contours of pathlines coloured by Total Temperature (Hydrogen)

Contrasting the results for hydrogen, the contours of pathline intensity coloured by total temperature for diesel fuel exhibit a broader and less intense flame front. The pathlines, coloured to represent total temperature variations, convey a distributed and varied temperature profile across the combustion zone. The swirling motion induced by the burner is evident, but the characteristics of the pathlines reflect the differences in combustion behaviour between diesel and hydrogen. The visualization of pathline intensity for diesel fuel provides insights into the airflow dynamics and temperature distribution, showcasing variations in the heat release pattern compared to hydrogen. While diesel combustion still benefits from the swirling motion, the pathlines indicate a more gradual and dispersed distribution of high temperatures, aligning with the expected characteristics of diesel combustion [14].

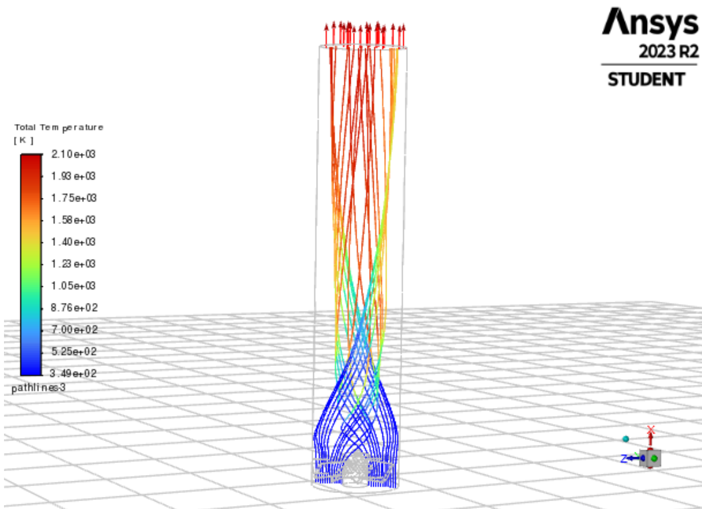

Fig. 8. Contour of Pathlines coloured by Total Temperature (Diesel)

4.2 Scaled Residual Graphs

The scaled residual graphs of the Discrete Phase Model (DPM) provide a quantitative assessment of the convergence and stability of the simulations for both hydrogen and diesel fuels. The scaled residual graph for the Discrete Phase Model during hydrogen combustion exhibits a rapid and consistent decline over the simulation iterations. This trend signifies the convergence of the DPM simulation, indicating that the computational model effectively captures the trajectories, dispersion, and combustion of hydrogen fuel particles within the swirling airflow [16]. The diminishing residuals reflect the robustness of the DPM model in representing the discrete nature of hydrogen particles, providing a high level of accuracy in simulating their interactions with the gaseous phase.

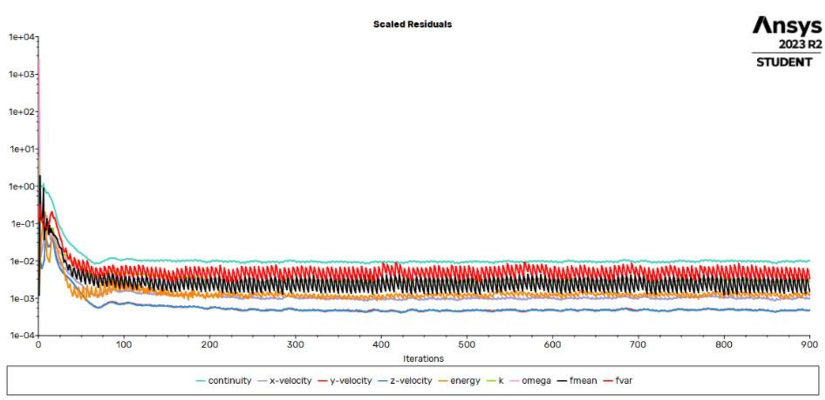

Fig. 9. Scaled Residual Graph (Hydrogen Fuel)

Similarly, the scaled residual graph for the Discrete Phase Model in diesel combustion follows a consistent decline, indicating the convergence of the DPM simulation for diesel fuel particles. The diminishing residuals affirm the computational accuracy of the model in representing the trajectories and combustion of diesel particles within the swirling airflow of the burner. The convergence of the scaled residuals in the DPM graph for diesel fuel underlines the model's effectiveness in simulating the behaviour of discrete fuel particles specific to diesel combustion [16,17].

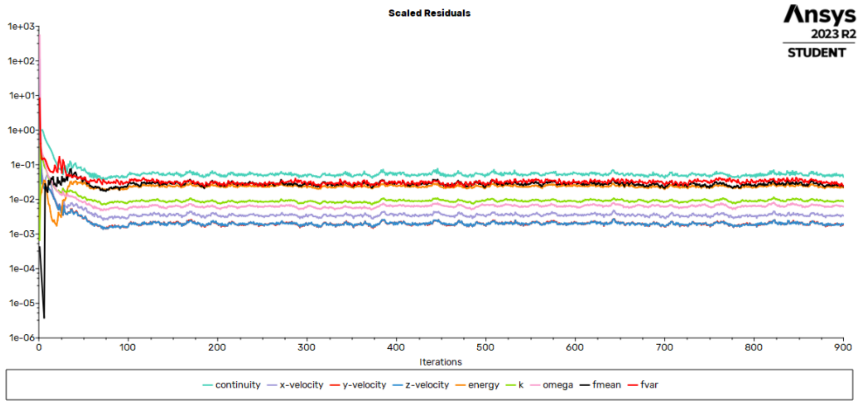

Fig. 10. Scaled Residual Graph (Diesel Fuel)

5 Conclusion

This study addressed the critical need for energy-efficient and environmentally conscious combustion technologies, particularly in the context of hydrogen as a fuel in swirl burners. Employing a Lagrangian approach with the Discrete Phase Model, the research investigated the dynamic behavior of particles in swirling airflow with a fixed swirl number, emphasizing the combustion properties of liquid hydrogen. The methodology involved designing burner and vane models with SolidWorks, meshing with Ansys for precise representation in simulations. Results revealed distinctive features of hydrogen and diesel combustion in the air swirl burner, showcasing the effectiveness of hydrogen combustion with concentrated and intense flame fronts and efficient fuel-air mixing. Diesel combustion, on the other hand, exhibited a broader and less intense flame front. Scaled residual graphs of the Discrete Phase Model validated simulation convergence and stability for both fuels, affirming the accuracy of the computational approach in capturing trajectories, dispersion, and combustion of fuel particles. This research provided valuable insights into the combustion behavior of hydrogen fuel in swirl burners, emphasizing its potential as a clean and efficient alternative, and extended our understanding of combustion processes, contributing to the foundation for further research in energy-efficient and environmentally conscious technologies.

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