CIÊNCIAS EXATAS E DA TERRA:

Conhecimentos didático-pedagógicos e o ensino-aprendizagem

Milson dos Santos Barbosa
(Organizador)

Atena Editora
Ano 2022

CIÊNCIAS EXATAS E DA TERRA:

Conhecimentos didático-pedagógicos e o ensino-aprendizagem

Milson dos Santos Barbosa
(Organizador)

Atena Editora
Ano 2022

Editora chefe
Profª Drª Antonella Carvalho de Oliveira
Editora executiva
Natalia Oliveira
Assistente editorial
Flávia Roberta Barão
Bibliotecária
Janaina Ramos
Projeto gráfico
Bruno Oliveira
Camila Alves de Cremo
Daphynny Pamplona
Luiza Alves Batista
Natália Sandrini de Azevedo
Imagens da capa
iStock
Edição de arte
Luiza Alves Batista

Ciências exatas e da terra: conhecimentos didático-pedagógicos e o ensino-aprendizagem

Diagramação: Camila Alves de Cremo
Correção: Yaiddy Paola Martinez
Indexação: Amanda Kelly da Costa Veiga
Revisão: Os autores
Organizador: Milson dos Santos Barbosa

Dados Internacionais de Catalogação na Publicação (CIP)

C569 Ciências exatas e da terra: conhecimentos didático-pedagógicos e o ensino-aprendizagem / Organizador Milson dos Santos Barbosa. – Ponta Grossa - PR: Atena, 2022.

Formato: PDF
Requisitos de sistema: Adobe Acrobat Reader
Modo de acesso: World Wide Web
Inclui bibliografia
ISBN 978-65-258-0422-4
DOI: https://doi.org/10.22533/at.ed.224220408

1. Ciências exatas - Estudo e ensino. I. Barbosa, Milson dos Santos (Organizador). II. Título.

CDD 507

Elaborado por Bibliotecária Janaina Ramos – CRB-8/9166

Atena Editora
Ponta Grossa – Paraná – Brasil
Telefone: +55 (42) 3323-5493
www.atenaeditora.com.br
contato@atenaeditora.com.br

CIÊNCIAS EXATAS E DA TERRA E ENGENHARIAS

Atena Editora
Ano 2022

DECLARAÇÃO DOS AUTORES

Os autores desta obra: 1. Atestam não possuir qualquer interesse comercial que constitua um conflito de interesses em relação ao artigo científico publicado; 2. Declaram que participaram ativamente da construção dos respectivos manuscritos, preferencialmente na: a) Concepção do estudo, e/ou aquisição de dados, e/ou análise e interpretação de dados; b) Elaboração do artigo ou revisão com vistas a tornar o material intelectualmente relevante; c) Aprovação final do manuscrito para submissão.; 3. Certificam que os artigos científicos publicados estão completamente isentos de dados e/ou resultados fraudulentos; 4. Confirmam a citação e a referência correta de todos os dados e de interpretações de dados de outras pesquisas; 5. Reconhecem terem informado todas as fontes de financiamento recebidas para a consecução da pesquisa; 6. Autorizam a edição da obra, que incluem os registros de ficha catalográfica, ISBN, DOI e demais indexadores, projeto visual e criação de capa, diagramação de miolo, assim como lançamento e divulgação da mesma conforme critérios da Atena Editora.

DECLARAÇÃO DA EDITORA

A Atena Editora declara, para os devidos fins de direito, que: 1. A presente publicação constitui apenas transferência temporária dos direitos autorais, direito sobre a publicação, inclusive não constitui responsabilidade solidária na criação dos manuscritos publicados, nos termos previstos na Lei sobre direitos autorais (Lei 9610/98), no art. 184 do Código Penal e no art. 927 do Código Civil; 2. Autoriza e incentiva os autores a assinarem contratos com repositórios institucionais, com fins exclusivos de divulgação da obra, desde que com o devido reconhecimento de autoria e edição e sem qualquer finalidade comercial; 3. Todos os e-book são *open access, desta forma* não os comercializa em seu site, sites parceiros, plataformas de *e-commerce,* ou qualquer outro meio virtual ou físico, portanto, está isenta de repasses de direitos autorais aos autores; 4. Todos os membros do conselho editorial são doutores e vinculados a instituições de ensino superior públicas, conforme recomendação da CAPES para obtenção do Qualis livro; 5. Não cede, comercializa ou autoriza a utilização dos nomes e e-mails dos autores, bem como nenhum outro dado dos mesmos, para qualquer finalidade que não o escopo da divulgação desta obra.

APRESENTAÇÃO

A coleção "Ciências exatas e da terra: Conhecimentos didático-pedagógicos e o ensino-aprendizagem" é um e-book que tem o intuito de fornecer *insights* sobre metodologias educacionais e aplicações tecnológicas para fomentar e desenvolver processos e produtos inovadores. O volume reúne estudos teóricos e práticos (revisões bibliográficas, relatos de casos, pesquisas científicas, entre outros) envolvendo cálculos matemáticos e afins para solucionar problemas e beneficiar diretamente a sociedade.

Neste contexto, a obra apresenta de maneira objetiva e didática estudos desenvolvidos por docentes e discentes de diferentes instituições de ensino e pesquisa do país. Os artigos englobam desenvolvimentos recentes no campo das tecnologias, energias renováveis, modelagens e simulações computacionais, algoritmos e softwares, bem como máquinas e equipamentos. Outra direção importante fomentada no e-book é abordagem utilizada para difundir os conhecimentos pedagógicos e o ensino científico nas ciências exatas e da terra.

Questões relevantes para a sociedade moderna são, portanto, debatidas a partir de uma perspectiva crítica, trazendo discussões de temáticas da área e propiciando um conhecimento específico e aprofundado para discentes, docentes e pesquisadores. Deste modo, a obra composta por capítulos que abordam múltiplos temas e com conceitos interdisciplinares da área de ciências exatas e da terra. Diante dessa oportunidade de aprendizagem, convido todos os leitores para usufruírem das produções da coletânea. Tenham uma ótima leitura!

Milson dos Santos Barbosa

SUMÁRIO

CAPÍTULO 11

NUMERICAL SIMULATION OF A CONNECTED-PIPE TEST RAMJET MOTOR

Data de aceite: 01/08/2022

Douglas Carvalho Cerbino
Universidade de Brasília, Faculdade UnB-FGA, Área Especial de Indústria Projeção A, Setor Leste, Gama, Brasília-DF
http://lattes.cnpq.br/8893737855566129

Olexiy Shynkarenko
Universidade de Brasília, Faculdade UnB-FGA, Área Especial de Indústria Projeção A, Setor Leste, Gama, Brasília-DF
http://lattes.cnpq.br/0072881392129534

ABSTRACT: This work presents analytical and numerical simulations of a ramjet engine developed at the Chemical Propulsion Laboratory (CPL) of the University of Brasilia (UnB) to aid its design and safety for future hot tests. The test facility comprises a connected-pipe test bench with a heater simulating the diffuser flow. The test bench's primary objective is to study the ramjet combustion chamber performance and the cooling wall effect provided by the presence of the flame holders. Transient time-averaged Navier-Stokes equations in two-dimensional form and the *k-ε* turbulence model describe the flow behavior. The non-premixed model based on GriMech 3.0 mechanism takes into account chemical transformations. Implementing the structured mesh and mesh sensitivity analysis yielded optimal simulation accuracy and time. The numerical simulation studies the motor performance in three flight regimes. The validation of the simulation results to analytical and numerical ones presented an acceptable level of data conformity. As a main result, CFD simulations proved the ramjet wall cooling concept with an efficient flame holder and separator. Consequently, more advanced simulations will be provided in the future resulting in recommendations for hot tests.

KEYWORDS: Ramjet, CFD, Non-premixed combustion.

SIMULAÇÃO NUMÉRICA DE UM MOTOR RAMJET DE TESTE DE TUBO CONECTADO

RESUMO: Este trabalho apresenta simulações numéricas e analíticas de um motor ramjet desenvolvido no Laboratório de Propulsão Química (CPL) da Universidade de Brasília para auxiliar o seu design e segurança para futuros testes quentes. A instalação de testes compreende uma bancada de testes do tipo tubo-conectado com um aquecedor simulando o fluxo do difusor. O objetivo primário da bancada de testes é estudar a performance da câmara de combustão e o efeito de resfriamento das paredes provido pela presença dos ancoradores de chama. Equações de Navier-Stokes transientes temporais-médias na forma bidimensional e o modelo de turbulência k-ε descrevem o comportamento do fluxo. O modelo de chama sem pré-mistura baseado no mecanismo GriMech 3.0 leva em conta as transformações químicas. A implementação de uma malha estruturada e de uma análise de sensibilidade de malha forneceram a acurácia e o tempo óptimos para a simulação. A simulação numérica estuda o motor em três regimes de voo distintos. A validação dos

resultados da simulação com os resultados analíticos e numéricos apresentaram nível de conformidade aceitável dos dados. Como principal resultado, as simulações fluidodinâmicas provaram o conceito de resfriamento das paredes do ramjet com ancoradores de chama e separador. Consequentemente, simulações mais avançadas serão providenciadas no futuro, resultando em recomendações para os testes quentes.
PALAVRAS-CHAVE: Ramjet, Fluidodinâmica Computacional, Combustão sem pré-mistura.

1 I INTRODUCTION

The performance analysis of air-breathing engines is more complex than conventional rockets because it strongly changes with the imposed flight conditions, such as Mach number, altitude, and angle of attack. In the engine development, before the complete propulsive system testing, the combustors of the ramjet are examined alone on the connected-pipe test bench (SARIŞIN, 2005). This type of test table is composed of a heater, which primary function is to simulate the diffuser flow, the combustion chamber, which promotes the energy increment in the system by combustion reactions, and the nozzle, which is responsible for accelerating the flow particles as a consequence of its momentum organization provided by the internal motor shape (ANDERSON, 2011). Figure 1 presents the engine schematics assembled at the laboratory.

The heater simulates the diffuser exit flow properties, such as pressure, temperature, and mass flux of the engine operating in natural conditions. The heater's primary purpose is to increase the flow temperature by the combustion process of a relatively small amount of fuel (SARIŞIN, 2005). Its functioning is similar to the combustion chamber, which will be described further. SHYNKARENKO et al. (2019) conducted an experimental investigation of hydrocarbon-based fuels. One of the results was estimating the vitiated air's thermodynamic state at the combustion chamber's entrance as a function of flight altitude and Mach number. Figure 2 shows the air stagnation temperature and pressure for different flight altitudes and velocities.

Injectors, flame holders, and an igniter are in a liquid ramjet engine combustion chamber. These three elements create efficient and controlled conditions and increase the system's temperature.

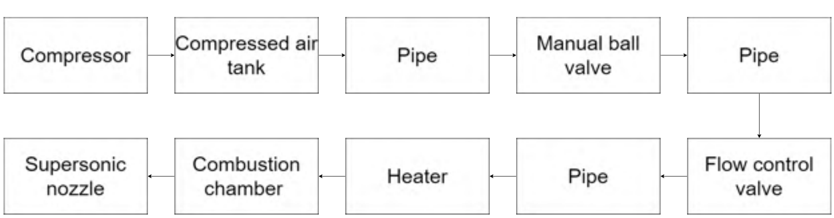

Figure 1. Engine schematics

A homogeneous mixture requires a well-distributed injector pattern. At the engine assembled at the Laboratory, the 304L stainless steel ring collector has the injectors evenly spaced across the circumference. The ignitor's objective is to begin the burning process in the combustion chamber. Finally, the flame holders generate recirculation zones for efficient combustion. It also allows the combustion to be self-sustained after the ignition and separate cold and hot flow regions. Avoiding the contact of hot gas areas with the engine walls, which could have structural damage due to high temperatures at the core of the combustion process, is also essential (BAILEY, 1960).

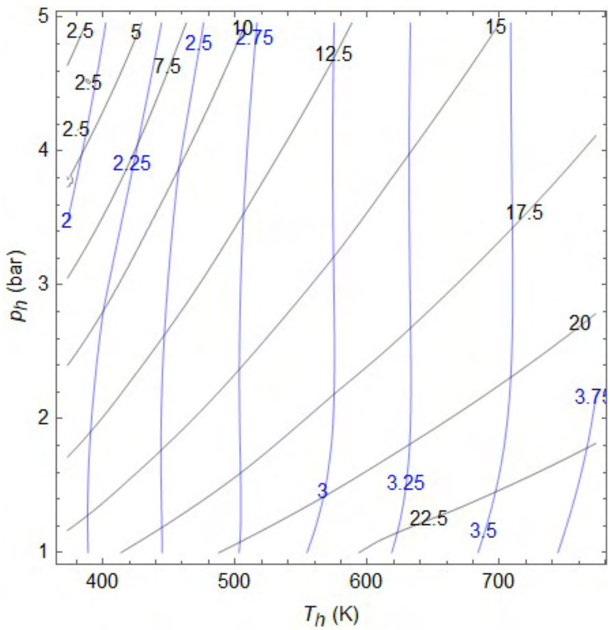

Figure 2. Temperature and absolute pressure as a function of flight altitude (km) - black, and Mach number - blue (SHYNKARENKO et al., 2019).

The nozzle's principal function is the flow's acceleration to generate as much thrust as possible. This effect is a consequence of the geometry change. The flow velocity change happens through the organization of the momentum of the highly diffuse particles at the end of the combustion chamber, so the thermal energy transforms into kinetic energy at the nozzle.

According to MATTINGLY (2006), the ramjet engine operates at the Brayton thermodynamic cycle, which has four principal transformations (CENGEL; BOLES, 2019). The connected-pipe test bench's thermodynamic cycle corresponds to the actual engine cycle in the combustion chamber, nozzle, and heat loss transformations. With the main objective of studying the combustion chamber, the transformation of heat increment is the main cycle parameter compared with simulations. In other words, the temperatures before and after the combustion process in the combustion chamber are compared. A detailed study of the engine's thermodynamic cycle and the detailed numerical simulation analysis shown in this paper for three flight regimes can be found in (CERBINO, 2021). Table 1 presents three test cases representing flight regimes chosen for the validation of the project. Table 1 also shows the engine's specific impulse I_{sp}, the temperature at the end of the heater T_h, and the combustion chamber outlet T_{max} obtained by analytical calculations.

Case No.	Case No.	Altitude (km)	I_{sp} (s)	T_h (K)	T_{max} (K)
01	2.5	14.0	2133	483	1869
02	2.75	16.0	1974	537.4	2009
03	3.0	18.0	2009	597	2131

Table 1 - Simulated flight regimes.

The current study originates from the research and development project about designing the ramjet motor for a highly-maneuvrable missile. The test motor created at the Chemical Propulsion Laboratory of the University of Brasilia (CPL) can operate at high-altitude conditions from 10 to 20 km and Mach from 2.5 to 3.0. The testing equipment creates such flight conditions on the ground utilizing the connected-pipe test bench. The works (AZEVEDO et al., 2018; FREITAS; SHYNKARENKO, 2020; AZEVEDO et al., 2019; SHYNKARENKO; CONTIJO, 2020) describe the infrastructure of the testing equipment. Besides the flow system schematics, other research is devoted to this motor's subsystems. For example, the papers (SHYNKARENKO; SIMONE 2020; SHYNKARENKO et al. 2015; FILHO; SHYNKARENKO; SIMONE; 2018; SHYNKARENKO et al.2019; SOUZA; SHYNKARENKO, 2017) describe not only studies on the ignition system design for the heater and main combustion chamber of the motor but also studies on the combustion of hydrocarbons in the flow path numerically. A small-scale solid-fuel ramjet motor is a predecessor of the current development. The works (SHYNKARENKO; CONTIJO, 2020; AZEVEDO et al., 2019) study such motor flow behavior and control. Work (CERBINO, 2021) shows advancements in evaluating global motor performance.

There are very few works in the area of the project. However, many researchers widely studied the fundamental flow processes and their numerical simulations in the last decades applicable in the current study. For example, Yi et al. (2019) provided the combustion characteristics of a CH_4/O_2 rapid mixed torch for a hybrid rocket motor. Haidn (HAIDN et al., 2016) studied hydrocarbon combustion for rocket applications. Oxy-fuel combustion of methane in a swirl tubular flame burner under various oxygen contents was checked (LI et al., 2017), and ignition characteristics and combustion performances of an oxygen-methane small thrust rocket engine in (JIAG; QING-LIAN; CHI-BING, 2018). The work (PAULY; SENDER; OSCHWALD, 2009) researches the ignition of a gaseous methane/

oxygen coaxial jet and work (MELVIN; MOSS, 1975) - structure in methane-oxygen diffusion flames. Combustion characteristics of the methane-oxygen diffusion flame in a model combustor and flammability characteristics of combustible gases and vapors were investigated (SEONG; JOON; JEONG, 2017; ZABETAKIS, 1965).

The validation of combustion in an axisymmetric natural gas furnace and turbulent mixing of two streams with different densities were studied (WESTBROOK; DRYER, 1981; UITTENBOGAARD, 1989). Work (HUANG; GROVES, 1976) examined turbulent flow with separation along an axisymmetric afterbody, and research (KAYS; CRAWFORD, 1993) simulated multicomponent species transport in pipe flow.

The principal motivation of the current study is research for the preparation phase for safe experimental tests. This work investigates the ramjet motor assembled at CPL by the numerical simulation and validates the results with analytical and numerical calculations. The work is innovative and novel from a computational point of view because its methodology utilizes a concept of the overall energy balance to simulate the flow properties inside the engine. It includes combustion energy liberation, its transformation to a thrust force, and consumption by the external sources according to the force balance described (CERBINO, 2021). In such a way, the flow simulation adapts to the flight regime simulated in the experiments.

This work aims to provide a numerical study of the chemically reacting, compressible viscous flows inside the ramjet engine. The following research is necessary to reach this objective: search for an appropriate numerical method, analyze the geometry, build and validate the structured mesh and organize numerical simulations.

2 | METHODOLOGY

The Authors used ANSYS Fluent software (ANSYS, 2013) to solve bi-dimensional axis-symmetrical transient time-averaged Navier-Stokes equations (ANDERSON, 2011) that describe the flow in ramjet engine. The *k-ε Realizable* turbulence model describes near-wall viscous processes in the computational volume. Simulation of similar-to-ramjet flow structures previously studied in a laboratory environment proved the efficiency of the turbulence model after its validation with experimental data. A comprehensive discussion about the flow model is provided in (BARDINA; HUANG; COAKLEY, 1997) and (ANSYS, 2013).

In the non-premixed combustion model, the reactants enter the reaction zone from two distinct streams (ANSYS, 2013). The flame type present in this model is the diffusion flame. The global reaction rate is typically limited by the molecular diffusion of the chemical species towards the flame front (WARNATZ; MAAS; DIBBLE, 2006). With the assumption that the chemical species react at the exact moment they mix at the molecular level, the problem is simplified to determine how the oxidizer mixtures with the fuel. The mixture problem is heavily simplified when one assumes equal diffusivities for all the scalars. Consequently, the solution focuses on the mixture of only one variable, *f*, which is the variable to be transported to the model. The set of equations solved by the CFD software is detailed in (ANSYS, 2013).

The domain edges use the following boundary definitions of ANSYS Fluent: the "mass flow inlet" of air at the left far end of the domain; two "mass flow inlets" of fuel located at the tip of the heater and combustion chamber injectors; the "axis" represented by the inferior line of the geometry; the "pressure outlet" at the far right end of the domain; and the remaining borders were defined as the "wall." Figure 3 shows the simulation domain and its details.

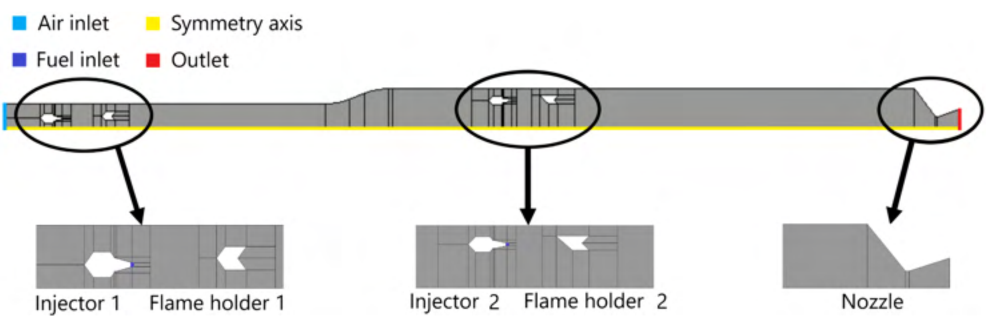

Figure 3. Computational domain.

The equation system uses the averaged Navier-Stokes equations for compressible viscous flows. The *k-ε Realizable* turbulence model with the scalable wall functions accounts for viscous effects and wall interactions. The non-premixed combustion model uses the Gri-Mech 3.0 chemical kinetics mechanism.

The coupled scheme with pseudo-transient and high-order term relaxation is selected in the methods. Monitors aided the simulation convergence analysis using the mass flux balance and the heat transfer rate on the walls as principal parameters. At first, it is solved in 2,000 iterations with automatic time steps using the option *verbosity* to check the initial stability and the flow time. After these iterations, a time step was one order of magnitude lower than the automatic time step (in this work, the time step is 10^{-5} s at this stage) to reduce the value of residuals and assist the convergence.

The spatial discretization has the following settings: least cell square-based for gradient treatment, first-order upwind for density, momentum, and discrete ordinates, second-order upwind for pressure, turbulent kinetic energy and dissipation rate, energy, mean mixture fraction, and mixture fraction variance.

The authors provide the validation of the flow simulation with analytical methods described in (ANDERSON, 2011), numerical calculation using the quasi-one-dimensional model in Rocket Propulsion Analysis (RPA) software, Ansys Verification Models (ANSYS, 2013), combustion analysis (WARNATZ; MAAS; DIBBLE, 2006), and the mesh sensitivity analysis explained in details in (CERBINO 2021).

3 | RESULTS

3.1 Mesh sensitivity analysis

Due to the axial symmetry of the engine, the numerical simulations used the axis-symmetric two-dimensional approach. The meshing algorithm utilized the face-meshing function on all faces of the domain. Figure 3 represents the domain division to apply the sizing function. All meshing zones are composed of quadrilateral elements aligned with flow direction (most favorable for CFD simulations to reduce the computational error). The mesh is refined near the walls, injectors, and flame holders, as these regions have higher parameter gradients. Thus, more minor elements are needed to represent effects such as the boundary layer, flamelets, and viscous effects.

Four different meshes are created with ANSYS Meshing to study the influence of grid refinement on the results. The first (coarse mesh) comprises approximately 102,000 elements; the second (medium mesh) has 183,000 elements. The third (refined mesh) has 333,000 cells, and the fourth (most refined mesh) has 512,000 elements. All meshes have the worst element quality in the range of 0.41; the mean element quality is around 0.98.

Figures 4 and 5 show the heat flux distribution along the walls and the temperature across the radial direction after the heater. The figures demonstrate that meshes 3 and 4 have almost overlapped results. Thus, mesh number three can be considered the optimal mesh for the system as the corresponding values do not differ significantly from mesh 4. The mesh has 2,009 divisions in the axial direction and from 47 to 237 at the inlet and outlet in the radial direction.

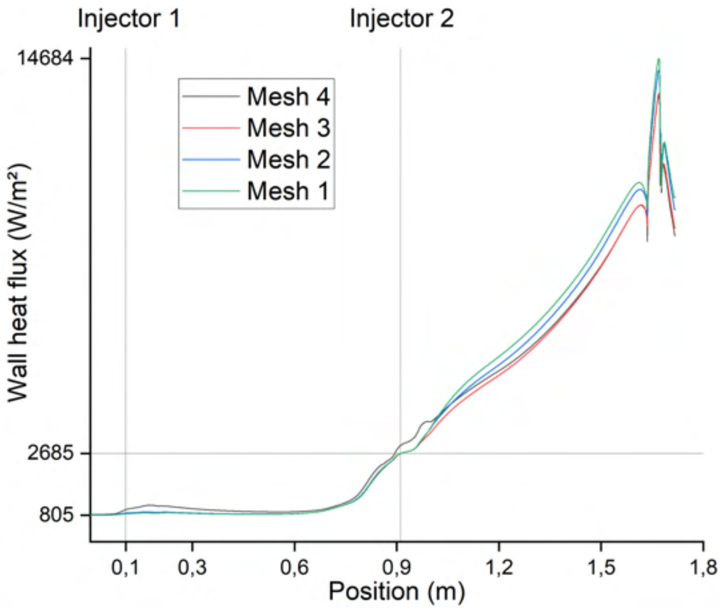

Figure 4. Heat flux on the engine wall.

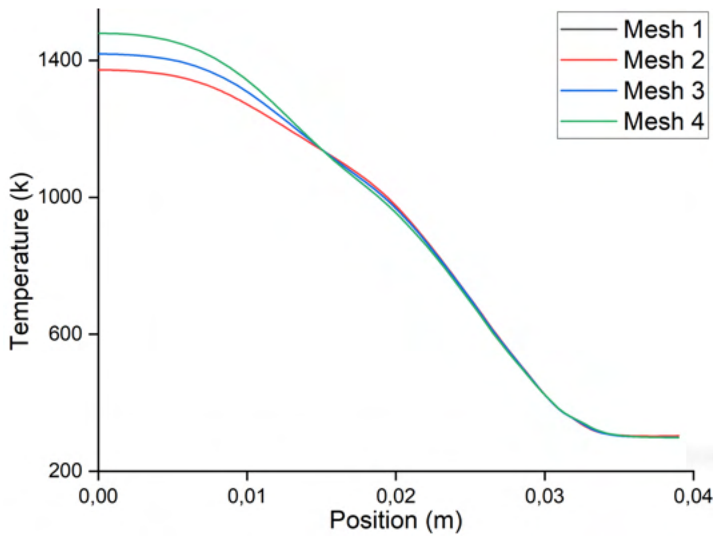

Figure 5. Radial distributions of temperature after the heater.

3.2 Temperature distributions

The area-averaged temperature after the combustion chamber throughout the entire radial direction showed a lower value for the mean temperature when compared to analytical results. Such a phenomenon occurs because of the flow separation effect. The flame holders generate an incomplete combustion zone near the engine walls yielding an excess of oxidizer and lower temperatures. Thus, to make an equivalent comparison between the simulation and analytical results, the mean temperature data is collected only in the reaction zone to produce an equivalent comparison between the simulation and analytical results. The simulation showed the area-averaged temperature after the heater of 494.6 K, 520 K, and 603 K for test cases 1, 2, and 3, respectively. After the combustion chamber, the temperatures were 1934.8 K, 1996.9 K, and 2030.9 K, respectively.

Additional Rocket Propulsion Analysis (RPA) simulations were conducted to validate the analytical model. The values of the maximum temperature of these simulations are 1888.7 K (test case 1), 2083.3 K (test case 2), and 2145.4 K (test case 3). Comparing the analytical model and RPA simulation results, a maximum deviation of 3.5% is obtained. A maximum deviation of 5.33% (test case 3) is obtained when RPA results are compared with the CFD simulations. This error increase is a consequence of two distinct situations: as the heater simulates the diffuser flow by a combustion process, the oxygen concentration of the air that reaches the combustion chamber is lower. Thus the energy released in the combustion process at the combustion chamber is slightly lower than the actual engine, also yielding to a lower final temperature when compared to the analytical result, and due to the flow separation of the flame holders mentioned in the previous paragraph.

Analysis of interior walls' temperature distributions showed a maximum value of 1089 K at the end of the combustion chamber (test case 2). Thus structural safety is guaranteed as the maximum temperature observed for all test cases near the axis of the combustion chamber and on the walls did not exceed the material thermal limit. Figure 6a displays temperature fields inside the computational domain for all test cases. Notably, temperature drop occurs at the transition zone between the heater and the combustion chamber in all cases. This process results from two zones with significantly different densities and temperatures. One area consists of a dense cold peripheral flow that protects the wall, and the other one of a low-density axial hot flow with intense combustion. Figure 6b demonstrates the mixing of two flows in the transition zone between the heater and the combustion chamber, decreasing the overall mean temperature. Figure 6c shows the density distribution inside the engine for test case 2.

It is important to note that from Fig. 6, a scale factor of 2:1 on the axial direction is applied for better visualization.

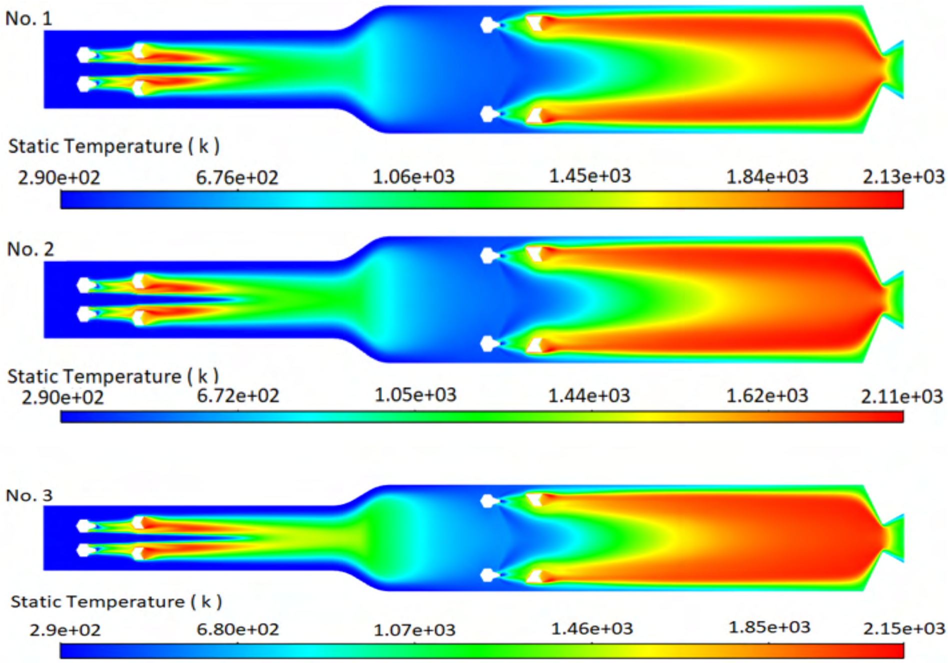

Figure 6. Simulated cases temperature contours.

3.3 Velocity, vorticity, and path lines

Figure 7 shows the Mach number, vorticity, and pathlines, respectively. Analysis of the pathlines determined the recirculation regions (lines in black in Fig. 7) near the flame holders, the combustion chamber entrance, and a small recirculation zone near the injectors. Low velocities observed on Mach number contours and high vorticity values at regions mentioned before confirm the recirculation zone locations.

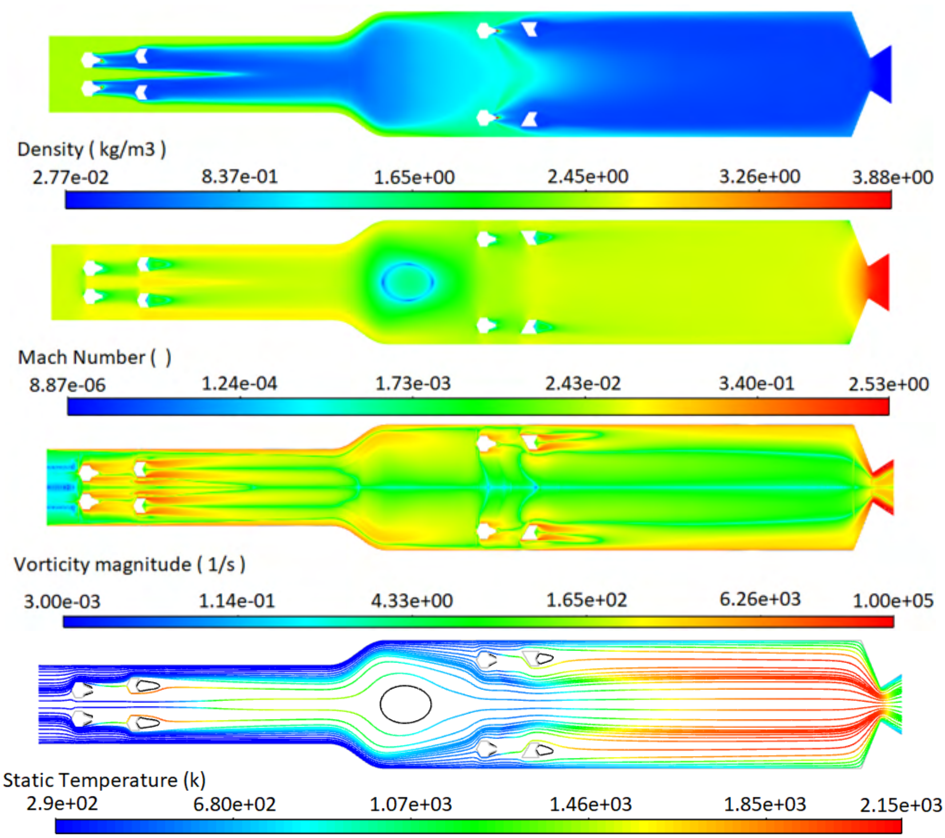

Figure 7. Density, Mach, vorticity contours, and pathlines.

4 I CONCLUSIONS

The bibliographic review made it possible to define the methods needed to make the numerical simulations properly. The bi-dimensional computational domain represents axis-symmetric flow in the engine. The structured mesh consists of quadrilateral elements refined according to the flow gradients in the boundary layer and the intense combustion regions. The mesh sensitivity analysis confirmed the mesh independence of results, ensuring the optimal accuracy and time for simulations. The chosen mesh presented close-to-optimal values for mean element quality as well as for the worst elements. Effects of temperature values after the heater and after the combustion chamber of simulations shown in section 3.2 presented a maximum deviation of approximately 4.7% when compared to analytical results presented in Table 1. Thus, the simulation results have a 5% tolerance deviation. The flame holders confirmed the presence of the flow separation regions and generation of the recirculating zones. Consequently, the simulation shows the efficient wall cooling by a cold gas layer near the wall. The combustion occurs in the engine's central region, which is self-sustained.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the University of Brasilia, FAPDF, CNPq, and the Chemical Propulsion Laboratory of UnB for the financial and technical support of the research project.

REFERENCES

ANDERSON, J. D. **Fundamentals of Aerodynamics**. McGraw-Hill Companies, Inc, Avenue of the Americas, New York, NY 10020., 6 edition, 2016.

AZEVEDO, V. A.; ALVES, I.; SHYNKARENKO, O.; VERAS, C. A. G. **Experimental investigation of high regression rate paraffin for solid fuel ramjet propulsion**. In 1 Congr. Aeroesp. Bras. – Edição Especial Plêiade, Foz do Iguaçu, PR, Brasil, 2018.

AZEVEDO, V. A.; ALVES, I.; SHYNKARENKO, O.; VERAS, C. A. G. **Experimental investigation of high regression rate paraffin for solid fuel ramjet propulsion**. AIAA Prop. and Energy 2019 Forum, Indianapolis, IN, USA, 2019.

BAILEY, F. W. **Flame holder construction**. Current Assignee: Curtiss Wright Corp. Inventor: F. W. Bailey. Attorney: V.D. Behu. 2,941,362. Filed: 2 Nov. 1953. Application granted: 21 Jun. 1960., 1960.

BARDINA, J. E.; HUANG, P. G.; COAKLEY, T. J. **Turbulence modeling validation**, testing, and development. Technical report, Moffett Field, California, 1997.

CENGEL, Y. A.; BOLES, M. A. **Thermodynamics: An engineering approach**. McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121, 9 edition, 2019.

CERBINO, D. C. **Simulação de fluxo dentro de um motor estato-reator**. Bachelor thesis, Universidade de Brasília - Faculdade do Gama (UnB - FGA), 2021.

FILHO, J.; SHYNKARENKO, O.; SIMONE, D. **Numerical study of the cooling effect inside a CH_4/O_2 torch ignition system for hybrid RM**. In 1 Congr. Aeroesp. Bras. – Edição Especial Plêiade, Foz do Iguaçuu, PR, Brasil, 2018.

FREITAS, L. C.; and SHYNKARENKO, O. **Experimental and analytical study of the cold flow inside a ramjet test engine**. J. Aerosp. Technol. Manag., 2020.

HAIDN, O.; CELANO, M. P.; MENG, L.; CHRISTOF, R.; SILVESTRI, S.; SLAVINSKAYA, N. **On methane/oxygen combustion for rocket applications**. Proceedings of the International Symposium on Innovation and Prospects of Liquid Propulsion Technology, Xi'an, China, 2016.

HUANG, T.; GROVES, N. **Propeller/stern boundary layer interaction on axisymmetric bodies: Theory and experiment.** David W. Taylor Naval Ship Research and Development Center Report, vol. 76-0113., 1976.

JIAQ, Z.; QING-LIAN, L.; CHI-BING, S. **Ignition characteristics and combustion performances of a LO_2/GCH_4 small thrust rocket engine**. J. Cent. South Univ., vol. 25, pp. 646–652, 2018.

KAYS, W.; CRAWFORD, M. **Convective Heat and Mass Transfer**. 3rd Ed. McGraw-Hill Book Co., Inc., New York, NY., 1993. [29] ANSYS Fluent Theory Guide. ANSYS Inc., 275 Technology Drive Canonsburg, PA 15317, 2013.

LI, B.; SHI, B.; ZHAO, X.; MA, K.; DINGJIANG, X.; ZHAO, D.; LI, J. **Oxy-fuel combustion of methane in a swirl tubular flame burner under various oxygen contents: Operation limits and combustion instability**. Exp. Therm. Fluid Sci., vol. 90, 2017.

MATTINGLY, J. D. **Elements of Propulsion: Gas Turbines and Rockets. American Institute of Aeronautics and Astronautics**, Inc, Alexander Bell Drive, Reston, Virginia, 2006.

MELVIN, A.; MOSS, J. **Structure in methane-oxygen diffusion flames**. Symp. (Int.) Combust., vol. 15, pp. 625–636, 1975.

PAULY, C.; SENDER, J.; OSCHWALD, M. **Ignition of a gaseous methane/oxygen coaxial jet**. Prog. Propuls. Phys., n. 1, pp. 154–170, 2009.

SARÇIN, M. N. **Design of a connected pipe test facility for ramjet applications**. Master's thesis, Middle East Technical University, Ankara, Turkey, 2005.

SEONG, B.; JOON, B.H.; JEONG, D. K. **Combustion characteristics of the methane-oxygen diffusion flame using swirl-coaxial injector in a model combustor**. Proceedings of the 53rd AIAA/SAE/ASEE Joint Propulsion Conference, 2017.

SOUZA, K.; SHYNKARENKO, O. **Development of a measurement system of temperature and pressure in the combustion chamber of a torch ignition system**. In Proceedings of the 24th International Congress of Mechanical Engineering, Curitiba, Brazil, 2017.

SHYNKARENKO, O.; AZEVEDO, V. A.; VERAS, C. A. G.; ALVES, I. **Experimental investigation of hydrocarbon based fuels in solid fuel ramjet propulsion**. 70th International Astronautical Congress (IAC), 2019a.

SHYNKARENKO, O.; CONTIJO, M. **Development of a thrust control system for rocket engines**. In 71st International Astronautical Congress (IAC), The CyberSpace Edition, 2020.

SHYNKARENKO, O.; FILHO, S. R. V.; ISHIOKA, I. S. K.; and HABL, L. T. C. **Design of a nitrous oxide/methane ignition system for hybrid rocket motor**. Journal of Dnipropetrovsk University, Series of Rocket Technology, 2015.

SHYNKARENKO, O.; SIMONE, D. **Oxygen–methane torch ignition system for aerospace applications**. Aerospace, 2020.

SHYNKARENKO, O.; SIMONE, D.; ANDRIANOV, A.; LEE, J.; BERTOLDI, A. E. M. **Experimental and numerical study of the flammability limits in a CH_4/O_2 torch ignition system**. Energies, 15, 3857, 2022.

UITTENBOGAARD, R. **Stably stratified mixing layer**. Data Report for the 14th meeting of the IAHR Working Group on Refined Flow Modeling, vol., 1989.

WARNATZ, J.; MAAS, U.; DIBBLE, R. W. **Combustion**. Springer-Verlag Berlin Heidelberg, Germany, 4 edition, 2006.

WESTBROOK, K.; DRYER, L. **Simplified reaction mechanism for the oxidation of hydrocarbon fuels in flames**. Combustion Science and Technology, vol. 27, pp. 31–43, 1981.

Yi, W; ZHANG, Z.; FUWEN, L.; WANG, N. **Combustion characterization of a CH_4/O_2 rapid mixed swirl torch igniter for hybrid rocket motor**. Aerosp. Sci. Technol., vol. 98, 2019.

ZABETAKIS, M. **Flammability Characteristics of Combustible Gases and Vapors**. U.S. Department of the Interior. Bureau of Mines: Washington, DC, USA, 1965.

ÍNDICE REMISSIVO

A

C

D

E

F

M

CIÊNCIAS EXATAS E DA TERRA:

Conhecimentos didático-pedagógicos e o ensino-aprendizagem

www.atenaeditora.com.br

contato@atenaeditora.com.br

@atenaeditora

www.facebook.com/atenaeditora.com.br

Atena Editora

Ano 2022

CIÊNCIAS EXATAS E DA TERRA:

Conhecimentos didático-pedagógicos e o ensino-aprendizagem

www.atenaeditora.com.br

contato@atenaeditora.com.br

@atenaeditora

www.facebook.com/atenaeditora.com.br

Atena Editora

Ano 2022