Three-Dimensional Modeling of Ablative Materials Exposed to Oxy-acetylene Test Bed

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ABSTRACT

In order to determine ablative properties, various labscale tests can be performed using different test apparatus. One of the more common test apparatus is the oxy-acetylene torch. In this study, the flow field of an oxy-acetylene test setup is examined using Ansys/Fluent 19.1 code. The heat transfer between the ablative surface and the combustion gases are compared with experimental results. Moreover, the results obtained from the CFD by applying different kinds of turbulence models are discussed. The calculated temperature and heat flux results are in reasonable agreement with the experimental results.

Keyword: computational fluid dynamics, ablative materials, heat transfer, oxy-acetylene test bed

1.0 INTRODUCTION

Ablative materials are used for various applications, such as solid rocket motors, missile launching systems, and thermal protection systems (TPS) for re-entry vehicles in the defense and aerospace industries. High-performance aerospace systems require innovative ablative material systems to meet their stringent requirements. For this reason, understanding the phenomena of the ablation mechanism is very essential. As seen in Figure 1, the ablation mechanism consists of convection, radiation, conduction, and diffusion of chemical species. As virgin material is pyrolyzing, the output gases of the pyrolyzing process spread over the surface of the ablative material, and a char layer is formed. This char layer behaves like a thermal barrier and its intensity changes according to the type of ablative material used.

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SAMPE Conference Proceedings. Charlotte, NC, May 20-23, 2019. Society for the Advancement of Material and Process Engineering – North America.

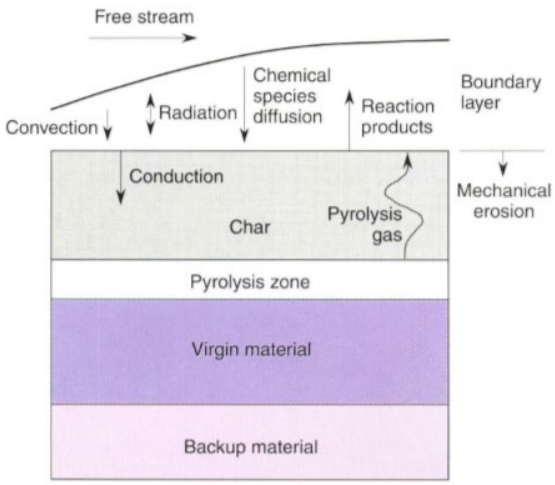


Figure 1. Heat and mass transfer of an ablative material during the ablation process [1].

Performance of ablative materials as inhibitors for aerospace applications and solid rocket motors can be examined by various methods. Experimental methods are especially preferred for the investigation of ablative materials. The oxy-acetylene ablation test method is a widely-used technique which characterizes ablation properties. In Figure 2, a standard oxy-acetylene torch test setup is shown. In this test set up, there are two gas lines that feed the system, one for the acetylene gas and the other for oxygen gas. Acetylene gas is used as the fuel, oxygen as the oxidizer, and the ratio of the mixture can be adjusted by the regulator. Fuel and oxygen are mixed in the mixing chamber and the output gases of the combustion process strike the ablative material. Ablative material is then eroded by a combination of chemical and mechanical ablation.

Bahramian [2] investigated the thermal degradation behavior of a composite-based ablative material used for TPS. Heat shield protection is tested by oxy-acetylene flame test setup; thermal degradation and backside temperature of the material is compared with the numerical model. Oxy-acetylene test setup is preferred, especially for the development of new materials, because it is economical and easy to utilize. Through the collaboration between The University of Texas at Austin and Dyna-Glass (now known as Techneglas), a new polysiloxane-silica fiber reinforced ablative was manufactured and tested in terms of combustion, flammability, and ablation properties [3].

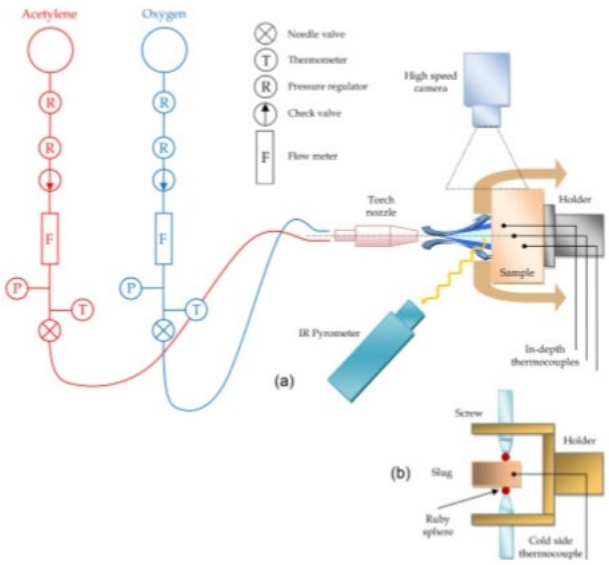


Figure 2. Standard oxy-acetylene flame test setup [4].

Marra et al. [5] performed numerical study of heat transfer between oxy-acetylene mixture and ablative samples. In their study, the performance of the TPS materials exposed to harsh environments were considered by modeling the burning procedure. A Computational Fluid Dynamics (CFD) model developed by Marra et al. [5] was used to simulate the combustion of an oxy-acetylene mixture occurring in a conventional welding torch. Heat flux and related temperature on the sample was calculated and compared with the experimental results. Three ablative materials, named EPDM/Kevlar, V44, and I-58 were examined under different temperatures by means of experimental and numerical results in Hung et al.'s study [4]. According to the study, after a certain heat flux value, the three different ablative materials do not show any change in ablation performance. Natali et al. [7] developed a one-dimensional model for the insulation capability of Elastomeric Heat Shielding Materials (EHSM). In their one-dimensional model, diffusion heat transfer is not considered, and the pyrolyzed gases have no effect on the exposed surface of the material. They left the surface without any interaction with the charred layer. This study is essential for researchers who are interested in modeling of ablative materials which are tested on OTB setup. Another experimental and modeling study of ablative materials was performed by Shi et al. [8] based on three-dimensional modeling. A three-dimensional thermomechanical model was implemented on Comsol Multiphysics software which is specialized

for complex structural components. The model predicts the temperature, pore pressure, and deformation behavior of the fiber-reinforced polymer composites.

2.0 EXPERIMENTAL SETUP

An oxy-acetylene test bed (OTB) was manufactured for the use of ablation tests performed in The University of Texas at Austin. A lathe chuck holds the sample in front of a welder's torch that produces oxy-acetylene flame calibrated to 1,600 W/cm^2. A sliding rail carriage allows quick exposure to and removal from the flame. Infrared (IR) and high-definition (HD) cameras are utilized to record recession, surface temperature, and surface morphology data. The OTB setup is shown in Figures 3 and 4. Testing was conducted on both 2D and 2.5D polymer fiber-reinforced composite compositions. Each sample was tested at a 1,600 W/cm^2 heat flux for 28 seconds for this study. A representative material test is shown in Figure 5. The OTB continuously collects data via a type-K thermocouple embedded 15 mm from the ablating face of the ablative plug to measure backside heat-soaked temperatures. A LumaSense Technologies ISQ5 two-color IR pyrometer and an M9104 Mikron IR video camera are used to measure surface temperature across the ablative surface throughout the test, and a DALSA DS-21-04m12-12e HD video camera captures changes on the surface during ablation testing. These data allow for the collection of surface temperature, mass loss, char yield, recession rate, and backside heat-soaked temperature.

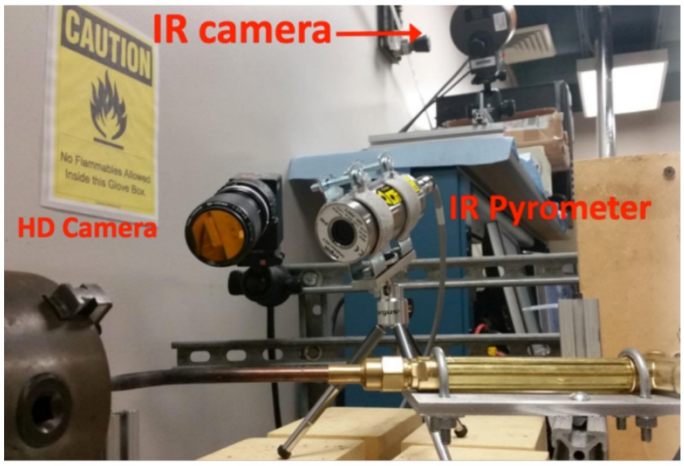


Figure 3. Instrumentation on an oxy-acetylene test bed at UT Austin.

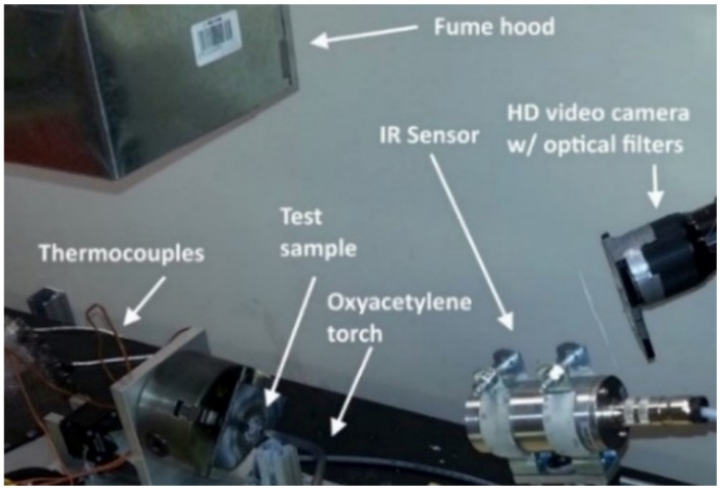


Figure 4. OTB test bed at The University of Texas at Austin.

To achieve a 1,600 W/cm^2 heat flux, a neutral 1.647:1 oxygen/fuel ratio was set up for the oxy-acetylene torch. This neutral flame reduces oxidation of the ablative material. Calibration was done with a No.4 Victor welding tip and a Vatell Gardon heat flux transducer (Thermogage). For preliminary testing, at least three ablative samples were created from each formulation with a 30 mm diameter and a thickness of 15 mm OTB test model. Representative samples are shown in Figure 5. Holes were drilled in the backside of each sample to accommodate a miniature (0.55 mm diameter) type-K thermocouple placed 15 mm from the sample side exposed to the flame.

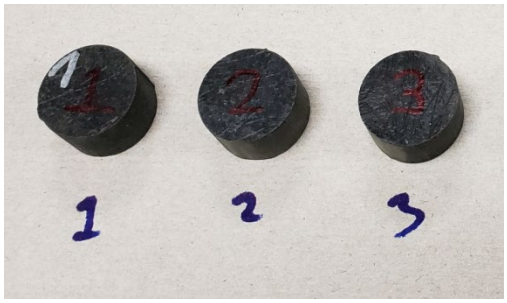


Figure 5. Representative ablative materials.

3.0 PHYSICAL PROBLEM AND DETAILS OF THE NUMERICAL STUDY

In this section, description of the physical problem and governing equations that were utilized during the solution of the problem are given in details. Details of the ablation phenomenon and the studies about this topic were mentioned in the introduction section.

3.1 Description of the Problem

Oxy-acetylene testing is an inexpensive way of screening materials before conducting the more expensive solid rocket motor ablation test. Performing validation of the material response (MR) (V&V) model by using experimental results provided by the OTB tests is a time-consuming technical study. Problem solving using numerical modeling of a system needs verification and validation steps. These verification and validation steps are performed using oxy-acetylene tests to simulate the desired test conditions.

3.2 Details of the Software and Modeling Studies

FLUENT Inc. (version 19.0) software is a strong engineering tool which is specialized for flow field and heat transfer analysis. Numerous industrial problems can be solved using this engineering tool. In this study, validation of the tool was performed by comparing the numerical calculations with experimental data. For the first step, a geometry which illustrates the physics of the problem is constructed. Constructed geometry is shown in Figure 6 and the details of the mesh structure are shown in Table 1. Steady-state fluid dynamics analysis was performed in order to pose a first look by means of showing the physics of the problem. Second order numerical scheme was chosen for all of the numerical studies in this study.

3.3 Validation Studies

For the validation of the software used, experimental tests using a heat gauge to measure heat flux of the OTB were chosen. Experimental heat flux results were compared with numerical heat flux calculations using the FLUENT code.

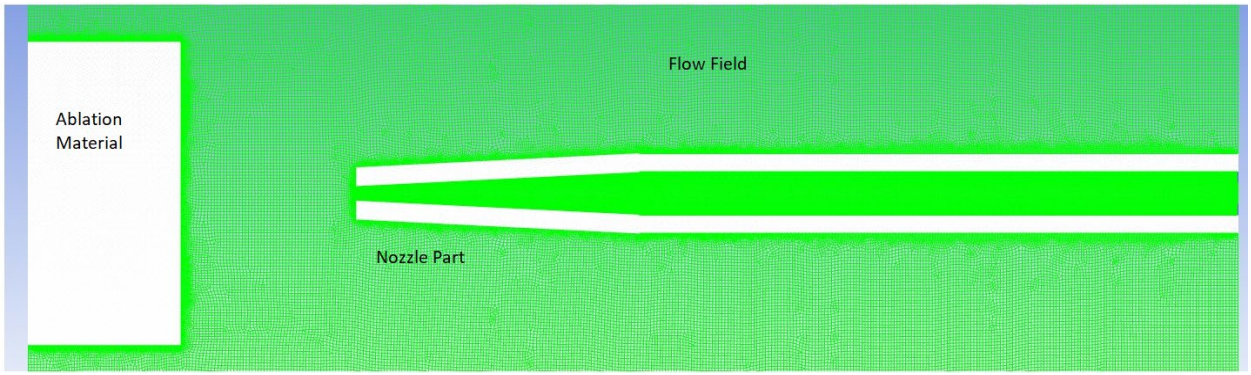


Figure 6. Mesh structure of the OTB test setup.

Table 1. Details of the mesh

Cell Number	Cell Type	Turbulence Model	Combustion Model
219,501	Hexagonal grid structure	SST-komega	Non-premixed combustion

Results of the experimental tests performed with the OTB test setup are given in Table 2. For the first case for the numerical validation, Test 1 was chosen. In Figure 7, heat flux versus distance of the experimental tests are shown. The heat flux value that occurs at ablation surface is inversely related to the distance between the torch and the ablative material.

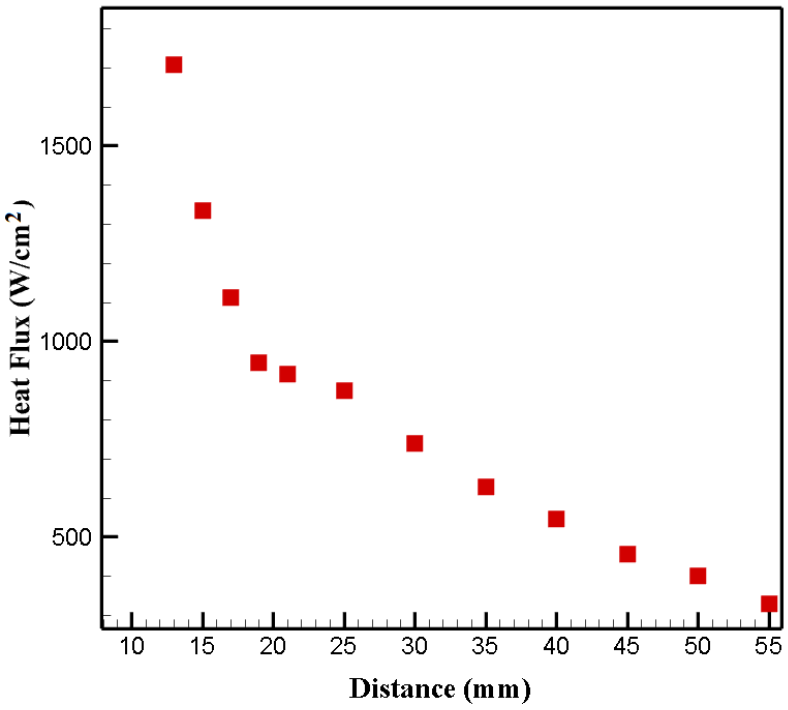


Figure 7. Heat Flux (W/cm^2) versus distance (mm).

Table 2. Details of the experimental tests

Test Number	Distance (mm)	Heat Flux (W/cm^2)
1	10	1794.9
2	12	1876.4
3	13	1708.5
4	15	1333.0
5	17	1111.0

6	19	945.2
7	21	915.6
8	25	874.4
9	30	739.5
10	35	627.7
11	40	545.3
12	45	456.3
13	50	401.1
14	55	330.3
15	60	288.9

Table 3. Boundary conditions

Boundary Type	Boundary Condition	
For oxygen	Mass Flow Inlet	0.386 kg/s
For acetylene	Mass Flow Inlet	0.2345 kg/s
Outlet	Pressure Outlet	1 atm
Ablation surface	Wall	-

The boundary conditions that were implemented into the software are acquired from the test conditions. Modeling studies were handled with the realistic experimental conditions in order to compare the test and numerical results. The heat flux gauge material that was exposed to the flame of the OTB test setup is made of tellurium copper.

3.4 Details of the Combustion Model

Combustion of the acetylene and oxygen can be modeled in two ways: one is a species transport model and the other is a non-premixed combustion model. In this study, the non-premixed combustion model is preferred for the modeling of combustion of the fuel and the oxidizer. In non-premixed combustion, fuel and oxidizer enters the reaction zone separately instead of mixing at the molecular level as actualized in premixed combustion [9]. The advantage of this model is in avoiding the nonlinear mean reaction rates. As the fuel and oxidizer are mixing, the chemistry can be modeled in three ways: chemical equilibrium, steady diffusion framelet model, and unsteady diffusion framelet model. In this study, chemical equilibrium model is preferred because of simplicity and this model's ability to produce more realistic flame temperatures than the Eddy-Dissipation model [9].

3.5 Heat Flux Validation and Calculations

In order to determine the heat flux between the combustion gases and the ablative surface, numerical heat transfer analysis was performed by using Ansys/Fluent 19.1. Validation cases were chosen from the heat gauge experiments. The OTB is set to various standoff distances from the ablative material. At known distances and known surface heat flux rates, the ablation rate of the materials is measured by the difference between initial and final thickness measurements taken before and after testing.

3.5.1 Test Case

In order to explain the numerical procedure of fluid flow and heat transfer calculations, a test case was chosen from the experimental setups, and details of the procedure are shown in this part. For this study, the standoff distance between test setup and ablative material chosen is 15 mm (Test 4, Table 2). In Figure 8, the velocity profile (m/s) of the OTB setup is shown. As seen, output gases hit the surface of the ablative material and are reflected from the surface to the sides. It seems for 15 mm standoff distance; the maximum velocity of the gas is approximately 1,500 m/s. The temperature profile (^{o}K) of the OTB test setup is shown in Figure 9. Mass fraction of the fuel (C_2H_2) is shown in Figure 10. Mass flow rate of the fuel is given as a boundary condition and acetylene and oxygen are mixed in the torch. Oxygen and acetylene ratios of the mixture are determined from the experimental conditions.

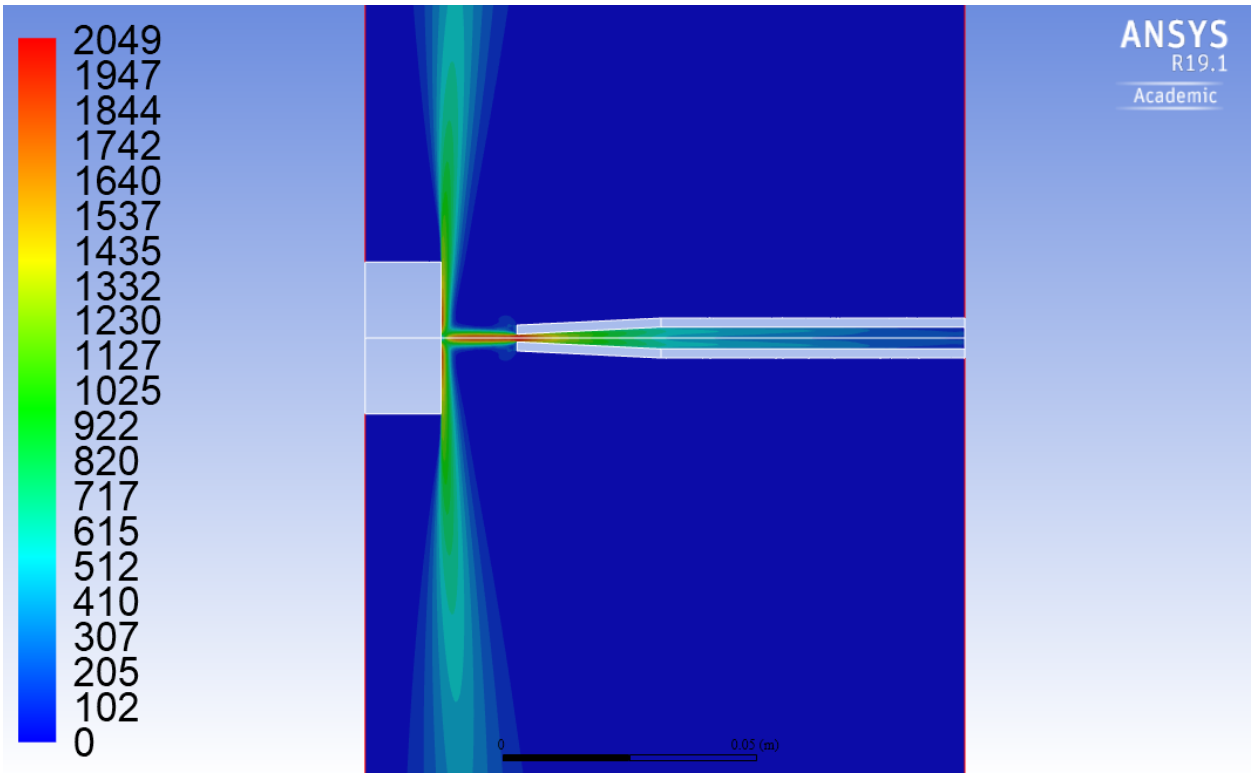


Figure 8. Velocity profile (m/s) of OTB setup.

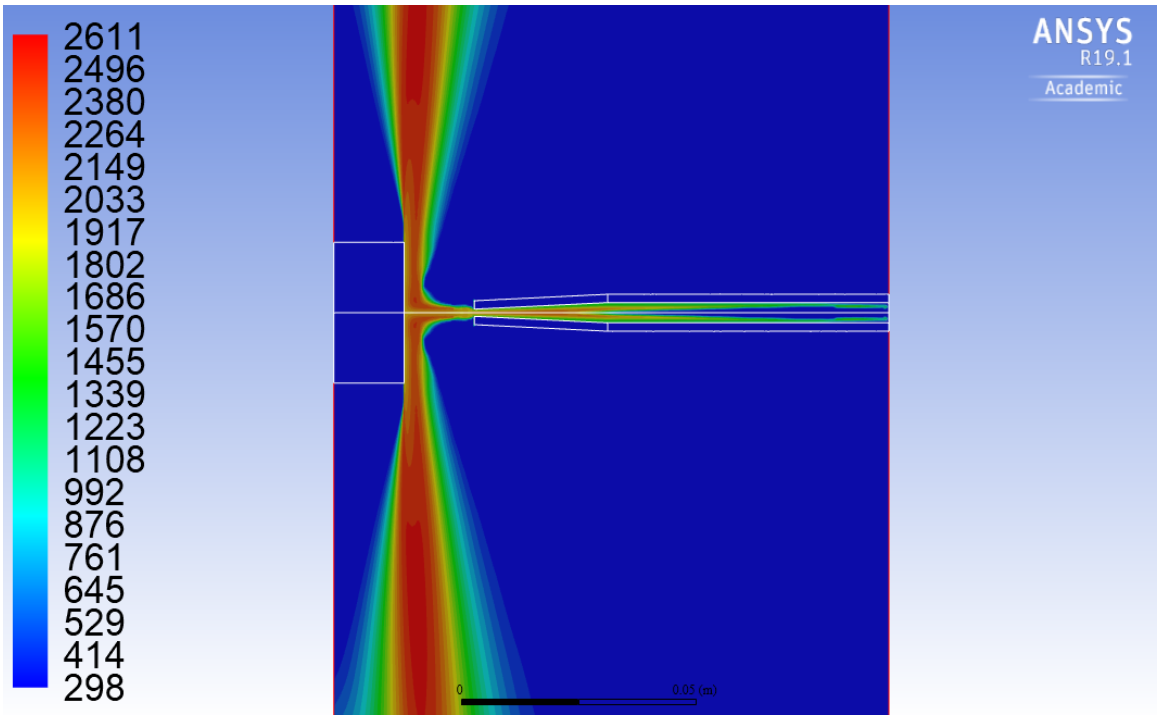


Figure 9. Temperature profile (^{o}K) of OTB setup.

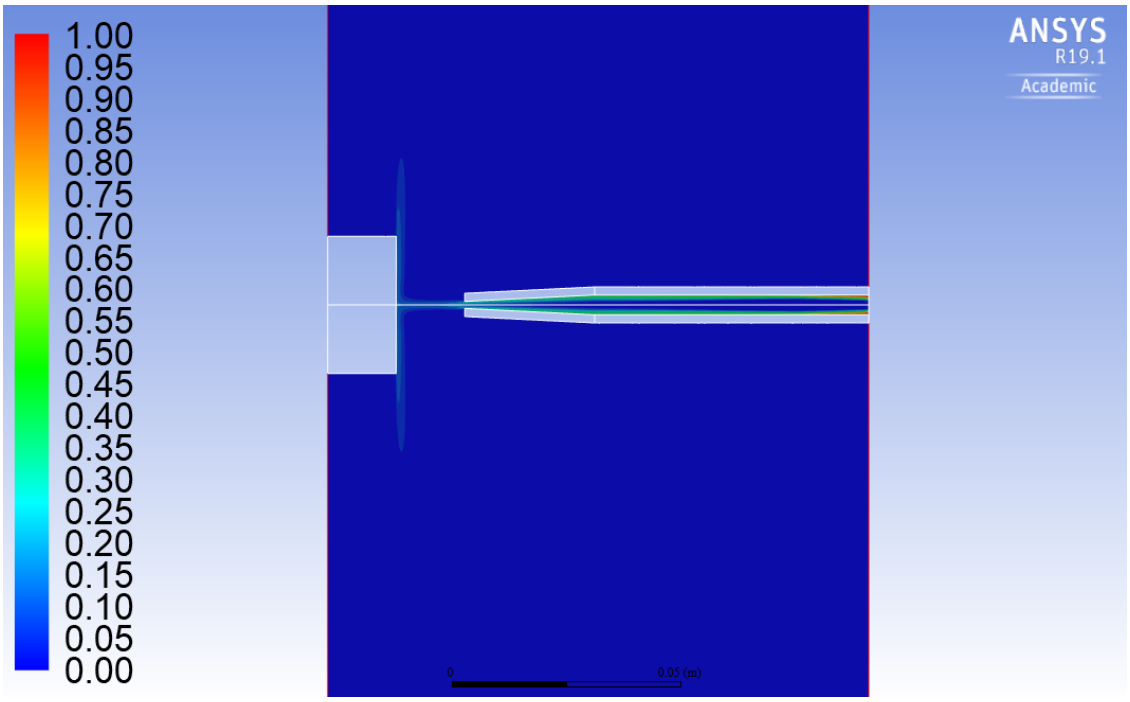


Figure 10. Mass fraction of fuel (C_2H_2).

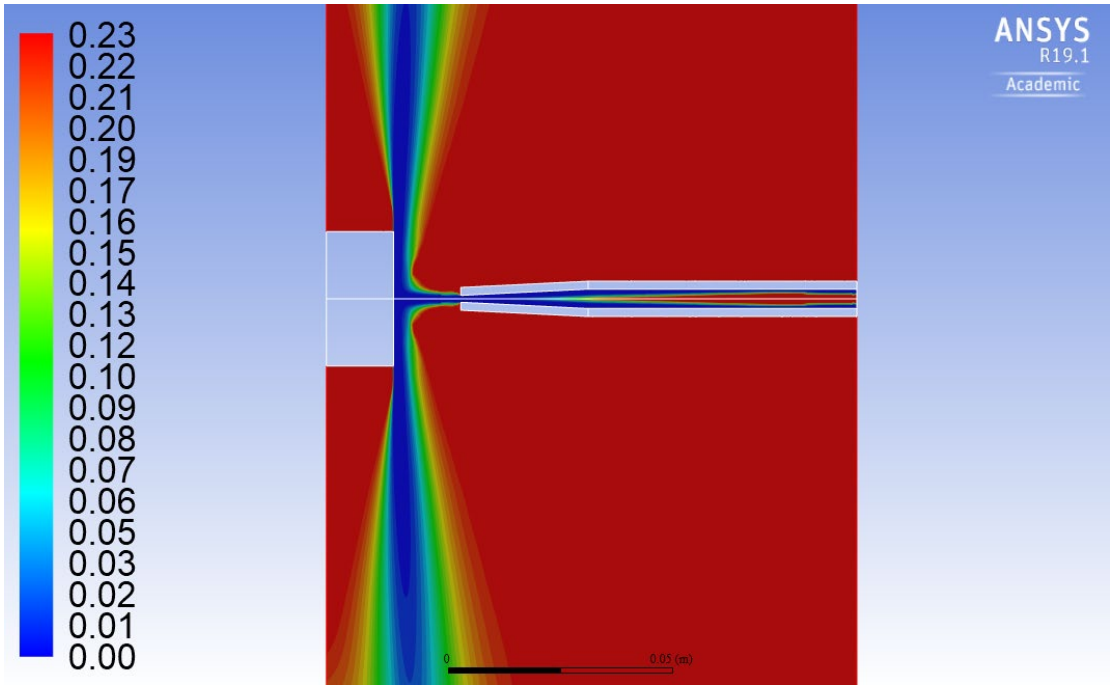


Figure 11. Mass fraction of oxygen (O_2).

3.5.2 Heat Flux Evaluation

In order to calculate the heat flux value of the ablative surface, the flow field of the OTB setup is determined and the momentum, turbulence, and pdf equations are not solved during the calculation of the energy equations. Steady-state calculation of the flow field is determined by k-omega SST turbulence model because fluctuating velocity fields can be small scale and high frequency, and direct simulations of these fluctuations can be very expensive in terms of computational calculation.

3.5.3 Turbulence Model Effects on Heat Flux Evaluation

Heat flux evaluation on the surface of the ablative material is performed for different kinds of turbulence models that are available in the Ansys/Fluent 19.1 software. Different kinds of turbulence models affect the solution of the flow field as well as temperature distribution of the OTB setup. The heat flux values are listed in detail in Table 4.

Table 4. Heat flux values using different turbulence models

Turbulence Model	Experimental Heat Flux Value (W/cm^2)	Numerical Heat Flux Value (W/cm^2)	% Difference
k-epsilon_std	1333.04	1530.4	14.8
k-omega standard	1333.04	1654.5	24.1
k-epsilon RNG	1333.04	1443.6	8.3
Transition-SST	1333.04	1465.9	10
Transition-k-kl-omega	1333.04	1467.6	10.1
Detached Eddy Simulation	1333.04	1472.4	10.5

3.5.4 Simulations and Discussions

In this study scope, different distances between the torch and the ablation material were studied. The numerical studies that were chosen for the comparison are shown in Table 5.

Table 5. List of Numerical Simulations

Test Number	Standoff Distance (mm)
1	10

4	15
7	21
10	35
12	45
15	60

In order to calculate heat flux values on the ablative surface, numerous runs were performed with Ansys/Fluent 19.1 software. In these studies, turbulence model effect which affects the solution of the problem was also examined. First of all, a test case was chosen for considering the problem. In the chosen case, the ablation material is set to 15 mm standoff distance from the torch and 1333 W/cm^2 heat flux was applied on the surface. Velocity profile, temperature profile, mass fraction of oxygen and acetylene are shown in the Figures 8-11 for this test case, and Table 4 shows the difference between the numerical studies and experimental studies based on heat flux. Different kinds of turbulence models were applied to the problem in order to study the effects on the results. It seems k-epsilon RNG turbulence model is the best fit for this problem. Also, according to the results, there is a slight difference between the numerical model and experimental model. This can be a result of mesh structure, underestimate prediction of temperature field of the problem or using non-premixed as a combustion model. These effects on the problem will be studied as future research. According to results of test case, k epsilon RNG turbulence model was chosen for turbulence calculations and other numerical studies were performed by using this turbulence model.

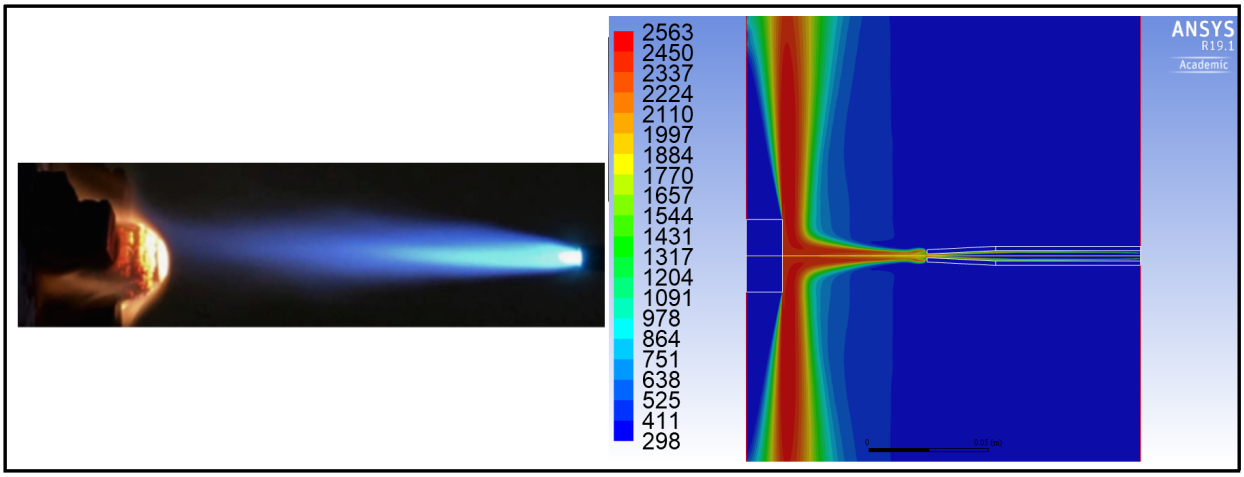


Figure 12. a) Picture of the experimental test 6 and b) Temperature profile for test 6.

Figure 12 shows the temperature profile of Test 6 and a picture of the sample burning. According to comparison of the two pictures, a core region of the combustion gases is seen just above the ablation surface. Combustion gases strikes the ablation surface and spread across the sides as also seen in the results of the numerical study. According to results after the combustion of the O_2 and C_2H_2, the maximum temperature of the flow field reaches approximately 2600 K. The temperature profile on the surface of the ablation material is affected by the thermal boundary of the surface of the ablation material. In this case, for determining the temperature profile, boundary layers were applied for the mesh process. The comparison between the numerical results and experimental results are shown in Table 6.

Table 6. Comparison of numerical and experimental results

Test Number	Experimental Heat Flux Value (W/cm^2)	Numerical Heat Flux Value (W/cm^2)	% Difference
1	1333.04	1530.4	14.8
7	915.6	988.99	8.0
10	627.7	615.44	1.96
12	456.3	444.38	2.61
15	288.9	326.4	13.0

Summary and Conclusions

This study presents a simulation of heat transfer in an oxy-acetylene test setup with different turbulent models. An axisymmetric numerical study with non-premixed combustion model has been conducted to examine the turbulent model effects on the heat transfer of the system. Oxygen (O_2) and acetylene gases (C_2H_2) are modeled as mass flux intakes to the system, and for the combustion process a non-premixed model of the Fluent 19.1 Software has been utilized. For the investigation of turbulent model effect on the problem, a test case has been chosen and examined using various turbulent models. Unfortunately no turbulence model is accepted universally for all kinds of problems, and different kinds of turbulence models are applied on problems according to physics of the problems, the level of accuracy required, the available computational resources and the amount of time available for the simulation [9]. In this study, K-epsilon RNG turbulence model seems the most appropriate model for solving this kind of problem because of the difference between the calculated numerical results and measured experimental results. The other reason for

choosing this turbulence model is that it is easy to apply and it does not need many computational resources. If the test configuration which can affect the flow field of the problem is changed, another test case study should be performed in order to determine the best turbulence model that fits the problem. According to the results in Table 4, the heat flux at the ablation surface, which is solved by using k-epsilon RNG turbulence model, agrees well with experimental results. The difference between experimental data and numerical simulations is under 10 % adapting this turbulence model which is quite good. According to the results of this study, the other experiments have been analyzed using this chosen turbulence model. Five experimental tests have been selected for the numerical simulations. According to Table 6, the results from Experiments 10 and 12 are very similar to the numerical results. In these tests, the torch setup is not set close to ablation sample. Experiments 1 and 15, which are the closest and furthest from the ablative sample, have a huge difference between the numerical simulations and experimental results. This could be caused by the distance between the ablation sample and torch which forms the flowfield. Flowfields belonging to these standoff distances may not be well simulated or for these distances another turbulence model may work better because of the prediction of the boundary layer of the ablation surface which affects the heat transfer.

It is an unfortunate fact that no single turbulence model is universally accepted as being superior for all classes of problems. The choice of turbulence model will depend on considerations such as the physics of the flow, the established practice for a specific class of problem, the level of accuracy required, the available computational resources, and the amount of time available for the simulation. To make the most appropriate choice of model for your application, you need to understand the capabilities and limitations of the various options

It would help if the authors gave more depth on the conclusion that the k-epsilon RNG turbulence model is the correct model. Specifically, it is unclear as to the “why” behind the conclusion that the k-epsilon RNG turbulence model is the correct model. For example, why is the k-epsilon yielding the correct results in some instances and not others? Why is the k-epsilon model correct (and not just that it happened to yield the right answers), but why is it physically reasonable that it would yield the most accurate results? Similarly, will the model continue to be the best choice of model if something about the test configuration is changed (i.e., fuel/air ratio, nozzle diameter, sample surface offset, etc.)?

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