Numerical Investigation of Swirl Enhancement for Complete Combustion in an Incinerator

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Abstract - Indeed, the entire country looks for to keep our environment neat and tidy. All form of wastes has some form of energy; normally it is incinerated to yield energy from it, and can be used to run gas turbines in power generation or mechanical drive applications. Incineration is one of the ways to control pollution, safe disposal of waste and need for landfill. Low emission level is great competitive in this world by burning all the given fuels in Engineering point of view. The work presented here is a numerical simulation of a cylindrical 3D combustion chamber, burning of all the given fuels without any residuals by providing Velocity Normal to Boundary (VNB) and Velocity Inclined to Boundary (VIB) with different approximations of fuel and oxygen by using CFD software, ANSYS-FLUENT™. The present work takes incineration gases, Toluene and Benzene as fuel. It is found that creation of swirl inside the chamber and supply of excess amount of oxygen to the chamber, provide a complete combustion of given fuel. The numerical predictions would provide useful information for further analysis in this area.

Keyword - Pollution control, Incineration, CFD optimization, CFD, Combustion chamber, Swirl

I. INTRODUCTION

During the last three decades the environmental consciousness has strongly increased across the globe. The focus is now to minimize the amount of wastes by adapting suitable process routes, if waste disposal cannot be avoided. The requirement of European Commission regulations is that only chemically inert material should be brought to the disposal site. The best way to make the waste inert is the thermal treatment. The most widely practiced method of thermal treatment is incineration. The wastes from production plants and waste water treatment plants are currently burnt mostly in specialized incinerators on the sites of the plants itself.

Incineration is a waste treatment process that involves the combustion of waste materials. It may be in the form of solid, liquid, gas or the combination of these three forms. Generally incineration is classified based on the chemical composition of solid, liquid, or gas and nature of characteristics. For example, Municipal incineration, Industrial waste incineration, Medical Waste incineration, etc. The emission from incinerators are divided into two categories namely, emission form complete combustion and emission from incomplete combustion. The exhaust of incinerators contains several pollutants such as oxides of nitrogen (NO_x), unburned hydrocarbons (UHC), carbon monoxide (CO), and particulate matter or smoke. Incineration efficiency is characterized by the occurrence of unburned hydrocarbons (UHC) and CO in the exhaust.

Jachim [1] conducted a study on gaseous emissions from waste combustion and highlighted some new developments which come under the common goal of reducing cost of the flue gas treatment by applying systems which combine the treatment of several noxious substances in one reactor – in the case of flue gas, desulphurization by reducing the amount of limestone consumption.

Incineration processes have well recognized benefits from both economic and environmental points of view (Giuseppe et al.[2]). Simulations of two incineration processes with and without flue gas recirculation was carried out by Giuseppe et al. [2]by using a commercial flow sheeting simulator. Jyh and Jian [3] made theoretical and experimental study on the emission characteristics of waste plastics, proposed a modified O_2 /RFG combustion technology in which the minimum pure oxygen is mixed with the recycled flue gas and air to serve as the feed gas, and investigated the effects of different feed gas compositions and ratios of recycled flue gas on the emission characteristics of CO_2, CO, and NO_X during the incineration of plastics. Anries et al. [4] proposed a combined cycle incorporating pressurized bed combustion of coal with pure oxygen and recycled flue gas followed by pressurized combustion of the flue gas using pure oxygen which is a process that produces electricity and heat with a high efficiency and a flue gas with a high CO_2 concentration, aimed at high efficiency coal conversion process with low CO_2 emissions.

Ade and Keum [5] developed a mathematical model of an oxy fuel combustion boiler system with flue gas recirculation. Hans et al. [6] experimented on municipal solid waste combustion in grate furnace and carried out simulations using FLUENT code, the turbulence temperature, flow and species distributions in the combustion chamber were predicted using a pilot waste incinerator test facility named TAMARA.

Chung and Ta-Hui [7] studied the operational characteristics of an air-oil furnace adapted for oxy-oil combustion, examined the effect of oxygen enrichment on the operational characteristics of heavy oil combustion in a retrofitted furnace with the flue gas recirculation, and evidenced the transition from air-oil to oxy-oil combustion along with the influence of combustion pressure did not bring negative impacts to the flame stability. Jiri [8] presented three case studies featuring applications of computational fluid dynamics (CFD) in the area of thermal waste treatment, with practical problems namely a performance evaluation of a fabric-filter bag with an add-on Venturi nozzle, a design homogenizing Vanes in a heat exchanger, and trouble shooting in a novel volatile organic compound treatment unit and thereby demonstrated the usefulness and the applicability of the CFD computations in the area of incineration. Roman et al. [9] developed a fully integrated unit for gas waste incineration of volatile organic compounds and carbon monoxide contained in polluted air.

John et al. [10] studied the gas, wall, and bed temperatures in a hazardous waste incineration kiln using a commercially available CFD based reacting flow code which included radiation heat transfer ,predicted that the peak bed temperature of the axial temperature profile, and of the gas temperature at the exit-plane were consistent with the measurements at a full scale waste incinerator during normal operation, and reiterated that the modeling studies provide useful information such as the relationship between available measurements and the temperature at the inaccessible locations inside a full scale kiln.

Robert et al. [11] made numerical model of Bio mass grate furnace aimed at optimizing the furnace geometry and secondary air nozzles regarding the mixing of fuel and air. Robert and Ingwald [12] emphasized the importance of using CFD for the optimization of industrial coal fire furnaces and gas burners. Due to high complexity of heterogeneous combustions of fixed or moving bio mass fuel beds, only few research projects have so far dealt with the introduction of CFD as a cost efficient tool in the optimization of bio mass grate furnaces. The major goal of CFD modeling is a techno-economic optimization of the furnace, reduction of furnace volume, optimal mixing of flue gas and air, reduction of erosion by fly ash as well as emissions by primary measures (Robert and Ingwald, [12]). Antonioni et al. [13] developed a model, simulated an existing municipal solid waste incinerator, and carried out optimization for both reactant feed rates and amounts of solid wastes formed in the acid gas removal process.

Research on improving performance of incineration has got more attention in the last decade and it was studied experimentally and numerically for various types of incinerators [1-15]. The output energy from the chamber will be considered to provide heat source for any applications in engineering. It is well known that creating turbulent flow inside the combustion chamber would enhance fuel-air mixture thereby improves the combustion process. The swirl can be created inside the chamber by altering the direction of air inlet and/or fuel velocities appropriately and the utilization of the swirling depends upon a proper mixture of air and fuel.

So the main aim of the present work is to enhance swirling characteristics inside the combustion chamber thereby improving the combustion efficiency to reduce un-burnt combustion products without any residuals. Here we change the direction of the air inlet with an inclination angle to create swirl for different combinations of air-fuel mixture. It was achieved by doing CFD analysis of flow through an incinerator including a combustion model.

II. MODEL DESCRIPTION

A. Computational Domain

The design feature for a 3D cylindrical combustion chamber consist of three inlets namely Velocity inlet 1, 2 and 3. The length of chamber is made 0.92m in order to provide proper mixing and to provide better swirl. The total height and width of chamber is 0.115m. Velocity inlet 1 or fuel inlet radius is 0.005m; Velocity inlet 2 and 3 or O_2 inlet radius are 0.01m and 0.11m respectively. The inlet 2 is provided circumference location within the inlet 3 in order to provide well swirl. Dimensional parameters of the chamber are shown in Table I and the computational domain is shown in Fig.1.

TABLE I
Dimensional Parameters of Chamber

S. No.	Name of the Portion	Typical Value (in m)
1	Inlet 1 (Rad)	0.005
2	Inlet 2 (Rad)	0.01
3	Inlet 3 (Rad)	0.11
4	Total length (L)	0.92
5	Total Height (H)	0.115
6	Total Width (W)	0.115

B. Boundary Conditions

The concept of working of the combustion chamber is divided into four categories as per our requirements. At Inlet 1, fuel is sent and at inlet 2 and 3, O_2 is supplied to initiate combustion. The value of velocity, directions and approximations of fuel, O_2 at all three inlets are different for different analysis. It can be divided into four cases.

1) Case 1: Velocity Normal to Boundary (VNB):

Velocity at all three inlets are normal to boundary of the chamber, with appropriate approximations of fuel and O_2 combinations, as shown in Fig. 2.

2) Case 2: Velocity Inclined to Boundary (VIB):

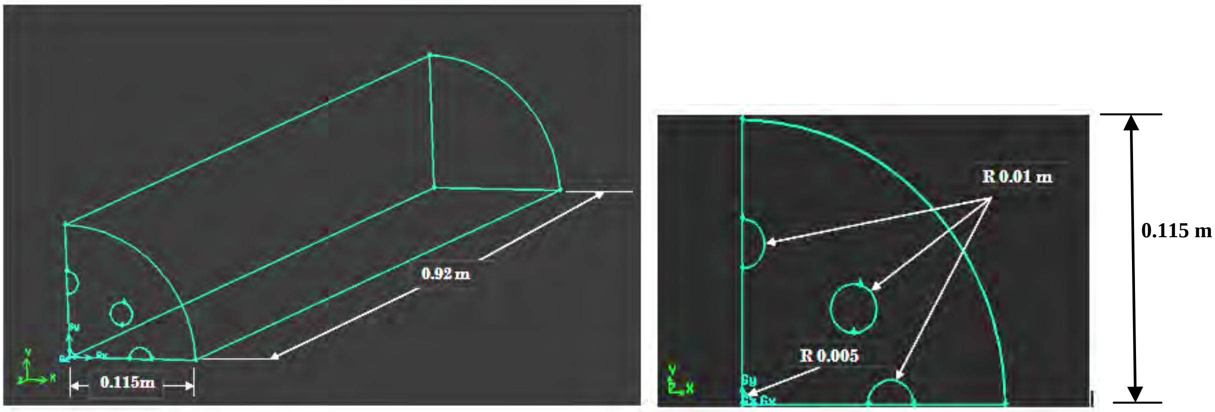
Velocity at inlet 2 is inclined to horizontal, and Inlet 1 and 3 are normal to chamber, with appropriate approximations of fuel and O_2 combinations, as shown in Fig. 3.

3) Case 3: VNB and different approximations of Fuel and O_2:

Velocities at all three inlets are normal to boundary of the chamber, with different approximations of fuel and O_2 combinations.

4) Case 4: VIB and different approximations of Fuel and O_2 :

Velocity at inlet 2 is inclined to horizontal, Inlet 1 and 3 are normal to chamber, with different approximations of fuel and O_2 combinations.



(a) (b)

Fig. 1. Schematic Diagram of Computational Domain; (a) Isometric view and (b) Front view

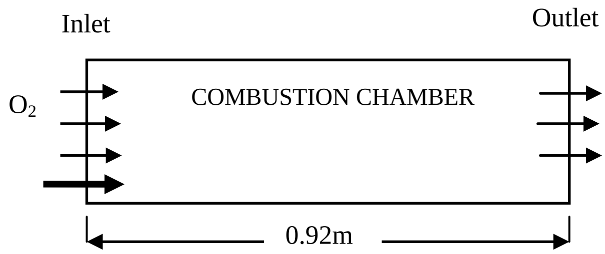


Fig. 2. Schematic Diagram of Velocity Normal to Boundary (VNB) - Side View

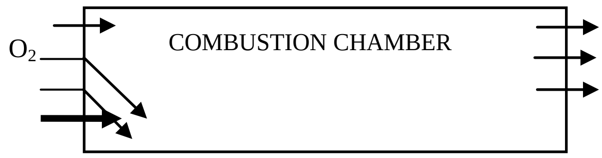
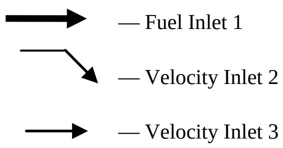


Fig. 3. Schematic Diagram of Velocity Inclined to Boundary (VIB) - Side View



C. CFD Simulation Frame Work

The unstructured (Tet/ Hybrid) mesh was used in the computations and boundary conditions for inlets 1, 2 and 3 are velocity inlet and for the outlet pressure outlet was selected. The two velocity boundary conditions are used namely, Velocity Normal to Boundary (VNB) and Velocity Inclined to Boundary (VIB). Periodic boundary condition is used for the chambers' flat side walls and no-slip boundary conditions are used for the remaining surfaces. Turbulence model used for the simulation was the standard *k-ε* model. Simulations are performed for the different combinations of fuel and oxygen percentage using commercial CFD software ANSYS-FLUENT^{TM}. The present work takes incineration gases, Toluene and Benzene as fuel.

The specific tasks necessary to accomplish the objectives are:

i. Design of Combustion chamber
ii. Meshing and Boundary conditions
iii. Numerical Investigation for the given combustion chamber.

III. RESULTS AND DISCUSSION

A. Case 1: Velocity Normal to Boundary (VNB) and Toluene (C_7H_8) as Fuel

In this case the inlet 1, 2 and 3 velocities are 45, 4 and 2 m/s respectively normal to chamber (Fig 2) and Toluene 50 %,(at inlet 1), oxygen 23% (at inlet 2&3) are given to chamber. The peak temperature, predicted using a constant heat capacity of 1000 J/kg-K, is over 2800 K. At the outlet, the temperature of gas is larger approximately 2800 K. It is seen that on periodic boundary face the temperature were too low approximately 300 K. The distribution of temperature from inlet to exit is shown in Fig 4. The character of fuel exactly at the end of combustion chamber all the Toluene gas burned. It is clearly seen at the exit of combustion chamber outlet. This is because of the correct approximations of fuel and oxygen mixture. It assures that, there are no incomplete pollutants as shown in Fig 5.

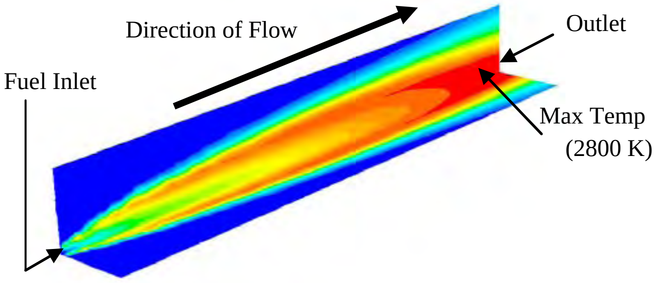


Fig. 4. Contours of Static Temperature in K (VNB - Toluene)

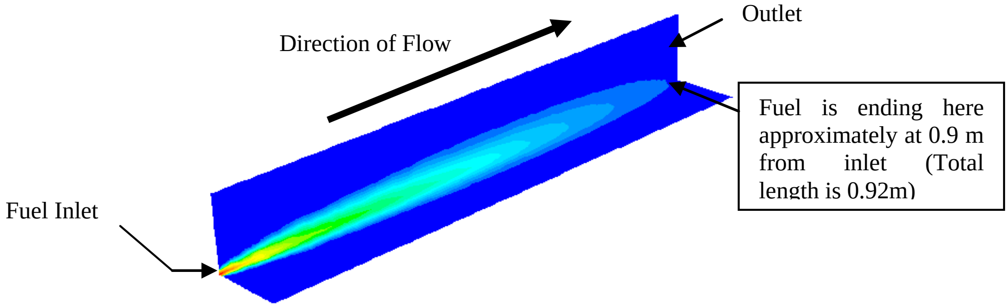


Fig. 5. Mass fraction of (C_7H_8) (VNB - Toluene)

The variation of static temperature along the flow direction for Case 1 is shown in Fig. 6. It indicates that the temperature increases as the distance increases form the inlet portions and reaches its maximum value of 2800 K at the outlet.

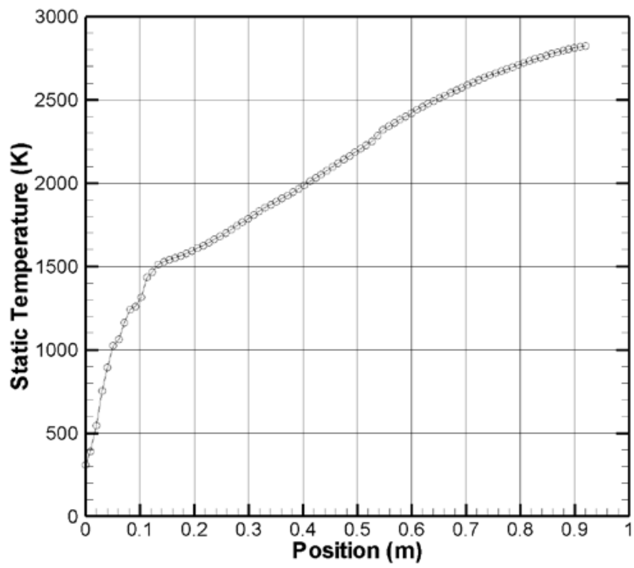


Fig. 6. Static Temperature vs Flow Direction (VNB - Toluene)

B. Case 2 Velocity Inclined to Boundary (VIB) and Toluene (C_7H_8) as Fuel

In this case the velocities of inlets 1, 2 and 3 are 45, -20, 5 m/s respectively inclined to chamber (refer Fig. 3.) and Toluene 50%, (at inlet1), oxygen 23% (at inlet 2 &3) was given to chamber. The peak temperature, predicted using a constant heat capacity of 1000 J/kg-K, is over 2800 K. This result is more or less same as in the Case 1, however the temperature distribution at outlet is different from Case 1, this is because of swirling effect created in this case (see Fig. 7.).

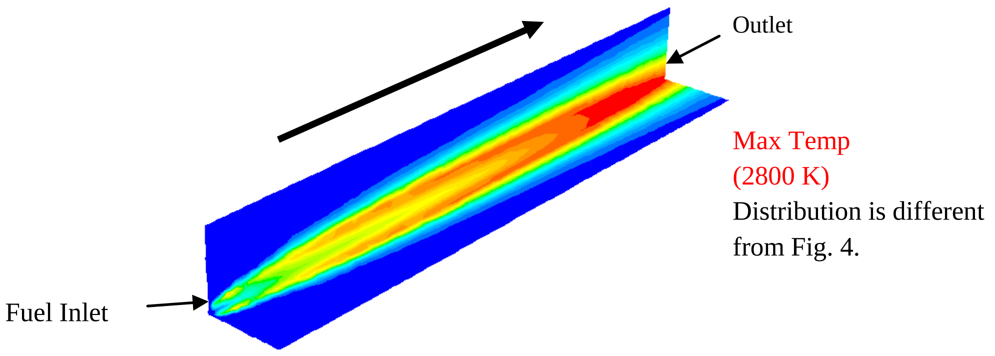


Fig. 7. Contours of Static Temperature in K (VIB - Toluene)

In this case all the given fuel is ending at a distance of 0.8m from inlet and total length is 0.92m. We can assure that, *there are no incomplete pollutants.* As compared to the case 1, here all the given fuel is consumed earlier due to swirl created by the inclined boundary which can be clearly seen in Fig 8. The velocity vector plot is shown in Fig 9 and the swirling is clearly seen at the entry region which is needed to enhance combustion process. It is evident from Fig. 8 that all the given fuel has been burnt at the earlier distance before reaching the exit section.

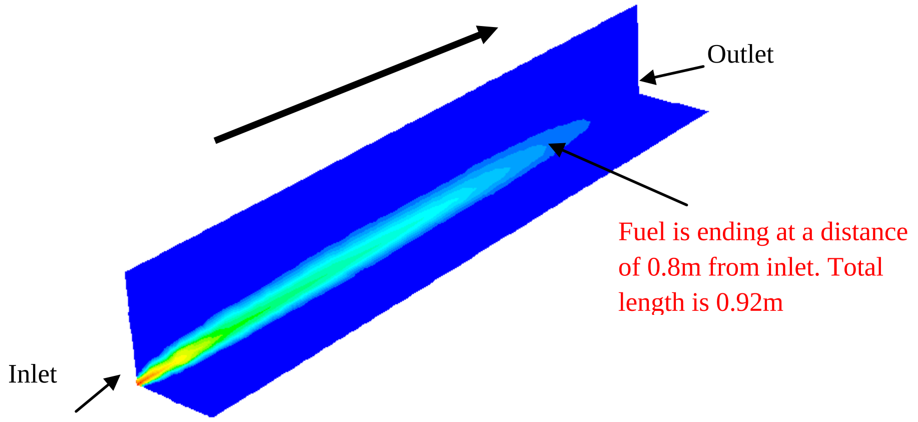


Fig. 8. Mass fraction of Toluene (C_7H_8) (VIB - Toluene)

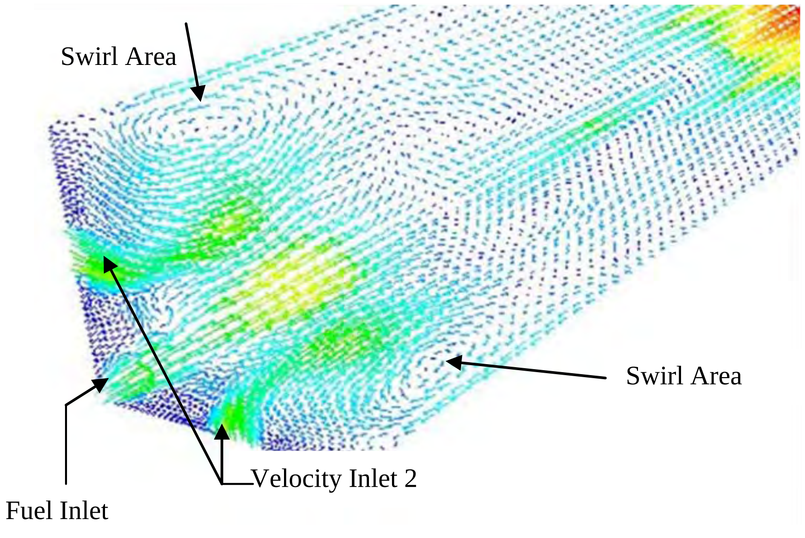


Fig. 9. Velocity Vectors Showing Swirl enhancement by Inclined Velocity Boundary (VIB –Toluene)

Similarly, various analyses with different fuel-air combinations have been carried out for Toluene and Benzene incineration gases for VIB and VNB conditions, as given in Table II. From the results, it indicates that combustion characteristics could be enhanced by adding more oxygen and the outlet temperature is reduced by increasing the velocity at inlet 2. It is also shows that 50% oxygen is good enough for complete combustion of 20% of Toluene whereas the same percentage of oxygen is not enough for complete combustion of 100% of

Toluene. It is evident that a proper combination of air-fuel mixture and also inlet velocity combinations are very important for better/complete combustion.

TABLE II
Different Analysis of Toluene (C_7H_8) fuel for Case 1 and 3 – VNB

Analysis	**$V_{N1,N2,N3}$ m/s**	**Toluene, O_2 %**	**Temp (T) K**		**Fuel Burning Condition**
			Max	**At Exit**	
1	45, 4, 2	20, 50	3840	1470	All fuel particles are burned
2	45, 4, 2	100, 50	5000	5000	Leaves at Exit
3	45, 4, 2	50, 23	2820	2820	All fuel particles are burned
4	45 ,10, 1	100, 23	2870	2870	Leaves at Exit

TABLE III
Different Analysis of Toluene (C_7H_8) fuel for Case 2 and 4 – VIB

Analysis	**$V_{I1,I2,I3}$ m/s**	**Toluene, O_2 %**	**Temp (T) K**		**Fuel Burning Condition**
			Max	**At Exit**	
1	45, -40, 5	50, 23	2790	1050	All fuel particles are burned
2	45, -40, 5	75, 50	5000	1470	All fuel particles are burned
3	20, -40, 5	75, 75	5000	1000	All fuel particles are burned
4	45, -20, 5	50, 23	2800	2800	All fuel particles are burned

TABLE IV
Different Analysis of Benzene (C_6H_6) fuel for Case 1 and 3 – VNB

Analysis	**$V_{N1,N2.N3}$ m/s**	**Benzene, O_2 %**	**Temp (T) K**	**Fuel Burning Condition**
1	20, 5, 3	30, 35	1390	All fuel particles are burned
2	20, 5, 3	100, 40	3910	Leaves at Exit
3	45, 10, 5	100, 30	3480	Leaves at Exit
4	60, 20, 6	50, 30	3290	All fuel particles are burned

TABLE V
Velocity Inclined to Boundary for Different Analysis (Fuel: Benzene-C_6H_6)

Analysis	**$V_{I1,I2,I3}$ m/s**	**Benzene, O_2%**	**Temp (T) K**	**Fuel Burning Condition**
1	45, -20, 2	100, 30	2620	Leaves at Exit
2	45, -40, 10	100, 20	2500	Leaves at Exit
3	45, -40, 10	100, 30	3440	Leaves at Exit
4	45, -40, 5	100, 75	5000	All fuel particles are burned

In Table III, the main results were particularly in all theses analyses fuel is burning within chamber without leaving out. Swirl plays an important role here. It may be noted that for the same combination of air-fuel mixture with different velocity inlet conditions changes the exit temperature. For example, the inlet velocity 2 is changed from 40 m/s to 20 m/s results in change the exit temperature from 1050 K to 2800 K, respectively.

The Tables IV and V, show the different analyses for Benzene with Velocity Normal to Boundary (VNB) and Velocity Inclined to Boundary (VIB) conditions. In Table IV, the main results were fuel is ending at a distance approximately 0.45m from inlet, more addition of oxygen at inlet 1 and 2 reduce the exit temperature and outlet temperature were to high except in analysis case one. In Table V, the main results were addition of oxygen can control, fuel leaving out of chamber and swirl not given any acceptable results, because for maximum addition of fuel 30% of oxygen is not enough to burn all the given fuel.

IV. CONCLUSION

The Numerical Investigation of Flow through an Incinerator was successfully carried out using commercially available CFD software ANSYS-Fluent^{TM}. Toluene and Benzene fuels were supplied to the designed combustion chamber, and analysis was carried out for different inlet velocity conditions (Velocity Normal to Boundary (VNB) and Velocity Inclined to Boundary (VIB)) with different approximations of fuel and oxygen.

The two incineration gases were well burned before exit without any residuals for all the four cases, similarly fuel leaves at exit of chamber in some analyses. For Toluene at VNB conditions were gives output temperature at acceptable level and without any residuals with fuel 50% and oxygen 80%. In some analyses output temperature was too high and also fuel leaves at exit. From the case 1 and 3 for VNB we got, more addition of oxygen could burn all the fuels, but too much addition of oxygen could reduce the output temperature and increase of inlet velocity 2 also could reduce the exit temperature. But in VIB conditions all the analysis, all the fuel particles were burned and fuel approximations was not more than 75%. In this analysis swirl played an important role in burning all the fuel with in a chamber, even at middle of chamber all the fuels were ended. This scenario where fuel has been burnt fully before the middle plane of the chamber was not seen in VNB conditions. Outlet temperature was also acceptable in VIB conditions.

For Benzene fuel, at VNB conditions maximum addition of fuel 100% with 40% of oxygen could not burn all the fuel and outlet temperature was also not in acceptable level, whereas for the same velocity inlet conditions with 30% Benzene and 35% Oxygen combinations, the combustion is complete within the combustion chamber and also low exit temperature at 1390 K. In other analyses of VNB condition, higher the inlet velocities, higher the outlet temperature are. For the same fuel at VIB conditions, maximum addition of fuel 100% with 20% oxygen could give acceptable temperature as compared to other analyses. But, in other analyses all the fuels were burnt resulting higher outlet temperature. In all the cases of Benzene, incomplete combustion is found except for a case with100% fuel and 75% Oxygen combination where all the given fuels were burned within a chamber without any incomplete pollutants.

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