



ORIGINAL RESEARCH ARTICLE

SIMULATION AND OPTIMIZATION OF MUNICIPAL SOLID WASTE INCINERATION FOR ENERGY RECOVERY IN MAIDUGURI, BORNO STATE, NIGERIA

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ABSTRACT

This paper presents an analysis, modelling and simulation of Maiduguri municipal solid waste powered electricity generation plant using ANSYS. Determination of the waste's combustion characteristics: physical, proximate and ultimate analyses using ASTM standard was carried out. Initial and boundary conditions were applied in respect of the materials and geometry in order to carry out a numerical calculation. The reduced scale physical model batch type MSW power generating plant was successfully constructed for use to validate the CFD analysis. The MSW was sorted, graded, sized and weighted before being fed into the designed batch type model incinerator to fire the boiler. The temperature and pressure of the steam generated were measured using digital thermocouples and pressure gauges so as to quantify the expected energy. A comparison of the simulated and experimental temperature results showed that while Area A had 1090. K, 1409.9 K and 1609.6 K, Area B had 1918.1 K, 1893.6 K and 1425.1 K, Area C had 1413.1 K, 1548.8 K and 1036.6 K during simulation against an average of 1641.9 K for Area A, an average of 1896.3 K for Area B and lastly for Area C, an average of 1641.9 K, using the batch type MSW incinerator. The R^2 value of 0.979 was observed for 5 kg load, 0.994 for 4 kg load and 0.999 for 3 kg load, for Area A. For Area B, the R^2 values range from: 0.992, 0.993 and 0.995 for 5 kg, 4 kg and 3 kg respectively. For Area C, the R^2 values range from: 0.998 for 5 kg, 0.996 for 4 kg and 0.987 for 3 kg. The constructed municipal solid waste power plant generated 6.4 V, 6.6 V and 6.5 V for Area A, B and C respectively for 33 minutes. A mathematical equation for the calorific value was developed using ANSYS, Ms Excel and was found to compare favourably, for up to 87.5% with the Model, and 87.40% when compared to the Dulong Berthelot's formula. The moisture content, the feed rate and the energy content of the MSW greatly affect the quantity of electricity generated from the municipal solid wastes of Maiduguri.

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1.0 Introduction

In any technology, the design process depends on a clear understanding of the fundamental scientific principles on which the design is to be based. These fundamental principles are usually expressed in terms of the governing differential equations of the process under consideration. The required design is then obtained by solving these equations subject to the appropriate boundary conditions, physical constants, input and output conditions. In incinerators, the main combustion-related design items are the burning bed of solid waste on the grate and the gas phase path, including the reactions which take place. Simulation is then needed to evaluate the performance of a designed plant at its virtual stage, thereby saving these large sums of money which may be wasted in the case of under-performing plant. Mathematical modelling, characterization and analyses of the MSW using analytical methods and other softwares has been receiving tremendous attention by researchers across the globe (Goodman and Teixeira (1990); Eriksson and Baky (2010); Sharmina et al., (2014); Ahsan et al., (2014); Akbarpour et al. (2016); El-Jummah et al., (2016); Ola and Göran (2017); Satoshi et al., (2018)). Resource constraints and sustained high fossil fuel prices have created a new phenomenon in the world

market. Biomass and municipal solid waste (MSW) have widely been accepted as important locally available renewable energy sources offering low carbon dioxide (CO₂) emissions (Seksan, 2011). In Nigeria, the extreme North- Eastern part of Nigeria typically Maiduguri, produces large quantity of waste that needs removal and disposal from the immediate environment. Maiduguri also experiences chronic shortage of electric energy, mainly due to the activities of insurgents and other terrors groups which hinder growth and development as well as the economic independence of the region. The waste generation for the year 2023 is estimated to at 2.63×10⁵tonnes using a waste generation rate of 0.53 kg/capita/day, base-year population of 1,328,100 and an annual growth rate of 2.40% for Maiduguri (Amulah et al., 2024). Presently, in the Maiduguri area there are several gaps, in the need for more waste studies to cover seasonality; gaps in studies coverage in accounting for material-specific treatment as well as gaps in quality of research design and consistency such as: seasonality and control for days of week, lack of local knowledge on incineration, gasification among others, and material-specific recycling tonnages. There are also gaps in basic compositional data: moisture content, feed rate, energy content, bulk density, etc. This investigation involves the application of modern computational tools that could largely help improve and better the understanding of large quantity MSW based modelling and simulation for use in electricity generation. In order to achieve these, there is need to determine the basic composition of the refuse produced by communities in Maiduguri, through physical characterization, proximate and ultimate analysis. Investigate performance parameters such as the moisture content, the feed rate and the energy content of the MSW. Develop and validate a mathematical model that will predict the moisture content, the optimum waste feed rate as well as energy content. Simulate the moisture content, the optimum feed rate and energy content using ANSYS, and design and construct a small scale physical model MSW power generating plant that will be used to validate the CFD analysis, as well as test and evaluate the performance of the MSW power generating plant.

2. Materials and Methods

For this purpose, a personal computer, HP laptop with Intel (R) Core (TM) i7-5600U@ 2.6 GHz processor and 12GB RAM, is used for modelling and simulation. It has Windows 10 64 Bit Operating System (OS). The softwares used are: CATIA V5-6 (R2018) (First-rate Mold Solution Co. Ltd, 2018) for modeling, ANSYS Fluent (R1 2023) (Sandeep, 2017) Workbench for meshing and simulation, and Microsoft Excel. An air blower (Abubakar et al., 2018) and a small-scale batch type model incinerator.

2.1 Incinerator sizing

The internal volume requirement excludes the ash pit and can be evaluated from (Oumarou et al., (2012); Yang et al., (2019)):

$$V_{i_{min}} = \frac{Q_{thr}}{258,750 W/m^3} \quad (1)$$

$$Q_{thr} = \frac{M_b}{Q_{av}} \quad (2)$$

where:

$V_{i_{min}}$ is minimum theoretical internal volume (m³)

Q_{thr} is total heat released (W)

M_b is the mass of refuse burned per hour (kg/h) and

Q_{av} is average heating value (kJ/kg).

The expression of the amount of municipal solid waste production is (Geet et al., 2019):

$$TotalMSW = MSW_{percapita} \times population \quad (3)$$

2.2 Incinerator Furnace Geometry

To effect complete combustion high velocity secondary air jets are required (Klasen & Goerner, 1999; Goerner, 2003). To assess the effects of MSW loading rates, a batch type fixed bed model of the incinerator would be more appropriate.

2.3 Air Ratios

The combustion conditions in the furnace need to be controlled to give near-stoichiometric conditions by splitting up the total combustion air to a primary air and secondary air ratio of 1.3:1.8 (Goerner, 2003). The burning of a fuel (e.g., wood, coal, oil, or natural gas) in air is a familiar example of combustion (Kavanaugh, 1984).



Oxygen starvation often leads to partial combustion of the carbon to CO rather than CO₂: Since combustion effectiveness is also a function of gas residence time, it is important that the air volume flow is not too great, otherwise the incinerator dimensions would need to be increased with consequent cost penalties (Akpeet *al.*, (2016).

2.4 Residence Time

Residence time is determined by the velocity of the gases and the distance they travel through the combustion chamber (Oumarou *et al.*, 2012) as shown:

$$t = \frac{V}{q} \quad (5)$$

Or

$$t = \frac{\text{chamberlength,m}}{\text{gasvelocity,m/s}} \quad (6)$$

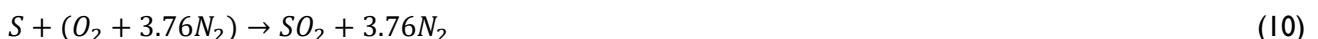
where t is residence time (s), V is combustion chamber volume (m³), q is combustion gas flow rate, (m³/s).

2.5 Combustion Analysis of MSW

MSW typically contains the following elements: c kg of carbon (C), h kg of hydrogen (H₂), o kg of oxygen (O₂), n kg of nitrogen (N₂), s kg of sulphur (S), m kg of moisture, a kg of ash (Akhator *et al.*, 2016):

$$c + h + o + n + s + m + a = 1 \text{ kg of fuel (MSW)} \quad (7)$$

The theoretical combustion reaction formulae of the combustible elements of municipal solid waste are expressed by the following chemical equations:



2.6 Combustion Air Requirement

Considering the theoretical combustion reactions for the MSW, characteristics in Tables (1, 2 and 3) (Babagana *et al.*, 2024), will be used to calculate the air to be supplied;

Table 1: Characteristics of MSW in Area A

Sample ID	Elements (%)					Moisture (%)	Ahs (%)	CV (MJ/kg)
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur			
Sample A1	46.22	0.21	41.85	11.64	0.08	39.24	10	4.3110
Sample A2	44.87	0.24	43.94	10.83	0.12	42.58	5.2	7.0610
Sample A3	43.14	0.20	47.09	9.46	0.11	41.70	4.80	10.0612

Table 2: Characteristics of MSW in Area B

Sample ID	Elements (%)					Moisture (%)	Ahs (%)	CV (MJ/kg)
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur			
Sample B1	47.91	0.23	41.42	10.34	0.10	37.49	11	19.8107
Sample B2	48.02	0.19	41.25	10.45	0.09	42.66	15.20	15.0559
Sample B3	47.08	0.20	42.15	10.50	0.07	49.90	13.20	5.7262

Table 3: Characteristics of MSW in Area C

Sample ID	Elements (%)					Moisture (%)	Ahs (%)	CV (MJ/kg)
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur			
Sample C1	45.90	0.55	47.07	6.35	0.13	38.15	10	7.5077
Sample C2	46.10	0.67	46.70	6.44	0.09	48.78	5.60	8.4217
Sample C3	46.40	0.76	45.93	6.77	0.14	42.40	4.0	4.5086

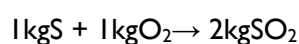
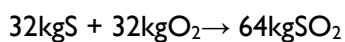
Carbon (C):



Hydrogen (H):



Sulphur (S):



To test and evaluate the performance of the MSW power generating plant, a small scale batch type physical model of an incinerator is constructed. The designed incinerator geometry has a width of 0.40 m, length of 0.50 m and a maximum height of 0.86 m. The geometry is meshed and value of meshes is determined using ANSYS fluent software and gives 0.17 m³.

The minimum temperature is 308 K corresponding to room temperature and the feed-in temperature of municipal solid waste as well as ambient temperature in the study area.

2.7 CFD Governing Equations

In order to calculate the flow field and the combustion of the waste burning inside an incinerator, it is necessary to have a system, which considers all of the involved phenomena (Arthur *et al.*, 2021). For the steady flow of a constant-property fluid, the equations that govern the flow around the air foil model are the continuity equation (14), and momentum equation (15).

$$\frac{\partial U_i}{\partial x_j} = 0 \quad (14)$$

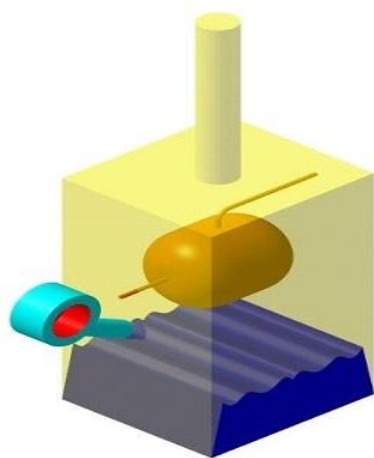
$$U_i \frac{\partial U_i}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\vartheta \frac{\partial U_i}{\partial x_j} - U_i U_j \right) - \frac{1}{\rho} \frac{\partial P}{\partial x_i} \quad (15)$$

where $i, j=1, 2, 3$, = mean velocity vector in x, y, z directions, P is static pressure, ρ is density and ϑ is kinematic viscosity.

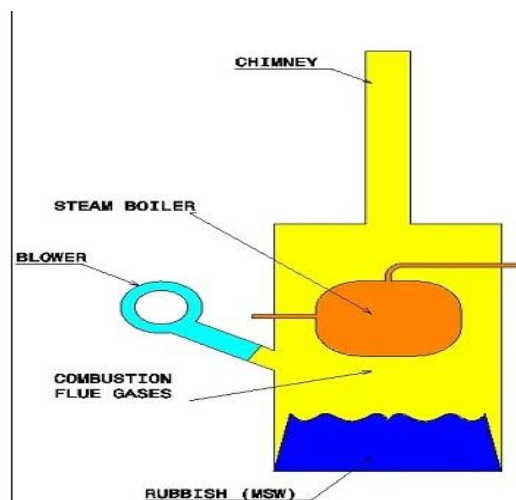
For a reliable simulation of an incinerator, it is completely essential to test the numerical procedures from computational and chemical error aspects (Pour *et al.*, 2020). To simulate the combustion with steam generation and determination of temperature and pressure, these steps were followed (i.e. Geometry (Domain) creation, Meshing, Setup and Solution).

2.8 Geometry (Domain) Creation

For simplicity of computation and minimize recourses, a 2D model was used and the simulation process was divided into two i.e. first simulating to optimize the combustion process and secondly simulating to determine the steam temperature at various operating pressure. To achieve complete combustion, sizes of the existing or proposed incinerator need to be specified to allow for air supplies calculations to be made. For this study, the following are considered: Length = 0.5m, Width = 0.4m, Height =0.86m and MSW height on the bed =0.2. The 3D model was imported into Design modeler of ANSYS FLUENT. The Model was converted into 2D and only the major fluid domains were taken into consideration for CFD as shown in Figure 1. All other parts were deactivated.



(a) 3D model



(b) 2D model

Figure 1: ANSYS Model representing the MSW Incinerator of the Study

2.9 Combustion Simulation and Meshing

The simulation of the combustion process of the MSW samples continue by considering the Combustion domain. Using the name selection tool of the ANSYS software, names were assigned to the boundaries for identification (ID) in the Design Modeler. The names ID are EXT_WALL, CHIMNEY_OUTLET, BLOWER_INLET, BED_INLET and INTERNAL_WALL.

The meshing was done for the domains lurching meshing on the workbench and fluid domain imported for the two project files. For the combustion domain the mesh element size was set to 0.0016 m and all other properties are left at default values. The mesh was generated with the generate tool. The number of mesh elements generated for the combustion domain was 1.3171×10^5 with 1.3334×10^5 mesh nodes.

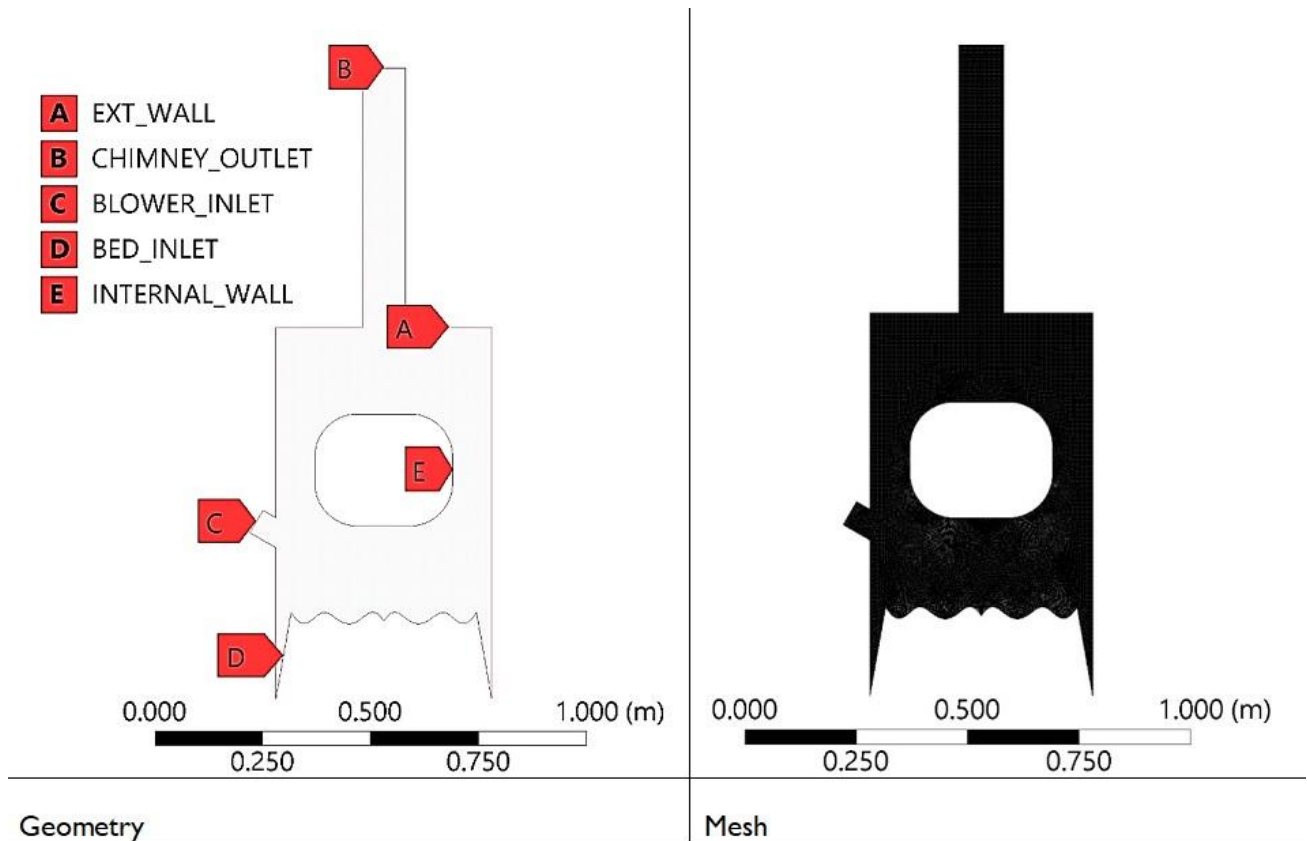


Figure 2: ANSYS Based Incinerator Geometry and Mesh with Boundary Areas

2.10 Setup and Solution

Species Model was enabled as a Non-Premixed Combustion. The **coal calculator** was opened in the species model to input the Proximate and Ultimate Analysis of Sample A1. The calorific value of the sample A1 was also inputted and assigning the combusting particle as *al_msw*. Figure 3 shows the inputted MSW characteristics of Sample A1 in the **coal calculator** window. (Note the Coal As-Received is the Calorific value). All other values are left at defaults.

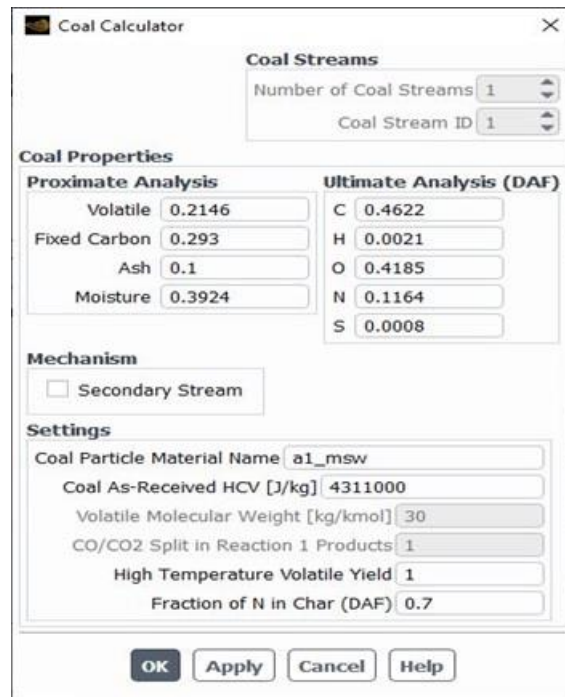


Figure 3: ANSYS Calculator Interface with MSW Characteristics of Sample A1

The setup and solution steps above were repeated with sample A2, A3, B1, B2, B3, C1, C2 and C3 i.e. with their corresponding characteristics. The maximum (optimized) value of *boiler_wall_temperature* obtained with the corresponding value of *blower_vel* were noted and recorded for each sample simulated. The optimized temperature would be used in the Steam generation simulation.

3. Results and Discussion

Figure (4) shows that the calorific value of the MSW yields a temperature of 1090.7K. Even with the control of the blower velocity, the pattern on the graphs does not change much. The heat is concentrated at the entrance of the furnace, where the supplementary air is coming in contact with the fuel for the first time in the furnace. As time increases and air blower velocity increases, so does the pattern on the ANSYS generated graphs. This is due to the high moisture level of 39.24%. This behavior could be due to the fact that some of the energy contained within the MSW is used to drive away the moisture and not used for other external uses like electricity generation or something else.

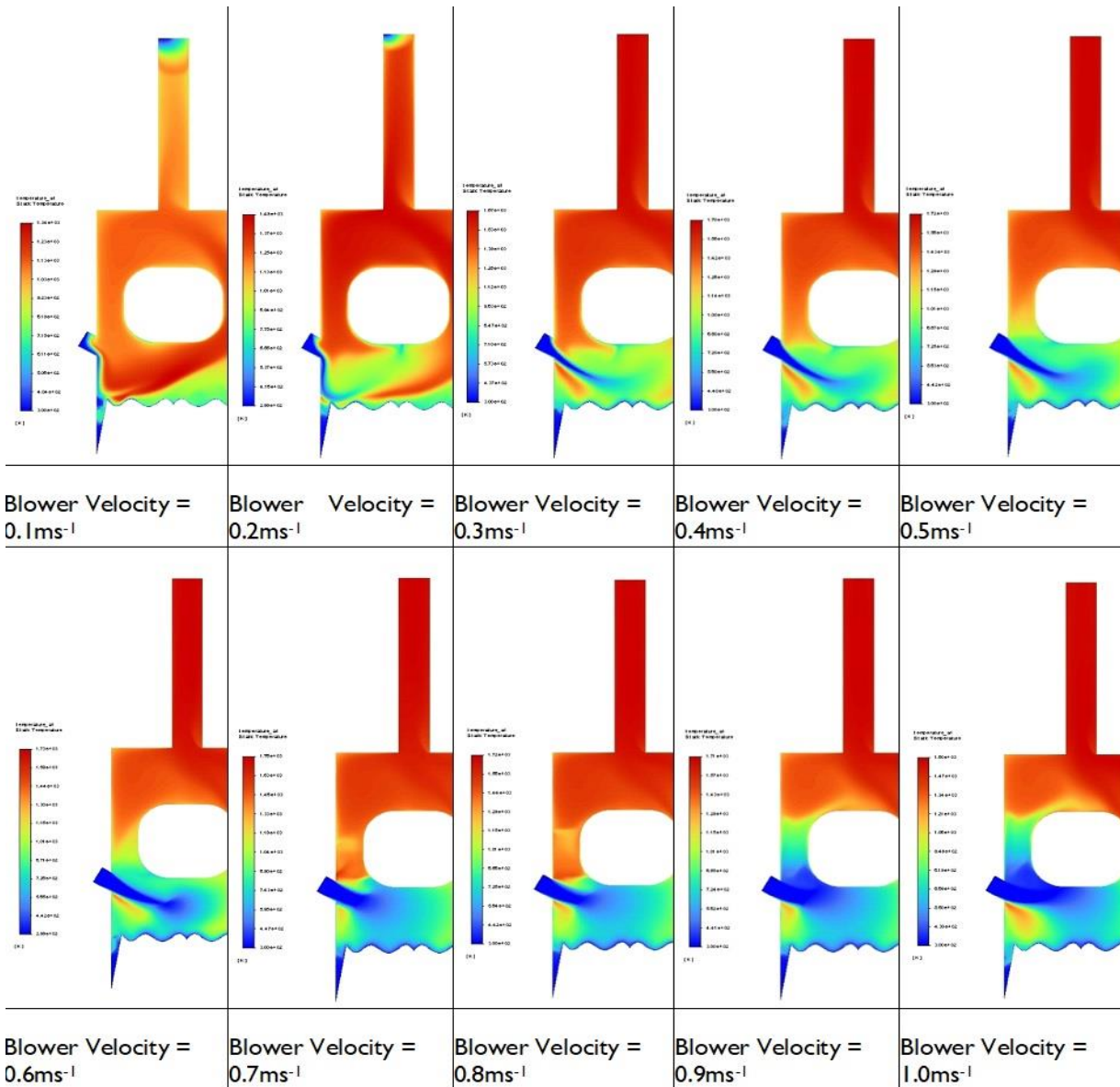


Figure 4: Simulated Temperature Contours of Sample A I

Similarly, Figure (5) shows a pattern, when the temperature rises to 1136.8K for moisture content of 42.58%. The control of the air blower velocity changes the pattern on the graphs at a lower speed. As time increases and air blower velocity increases, so does the pattern on the ANSYS graphs. This is due to the high moisture level. This behavior could be due to the fact that some of the energy contained within the MSW is used to drive away the moisture too.

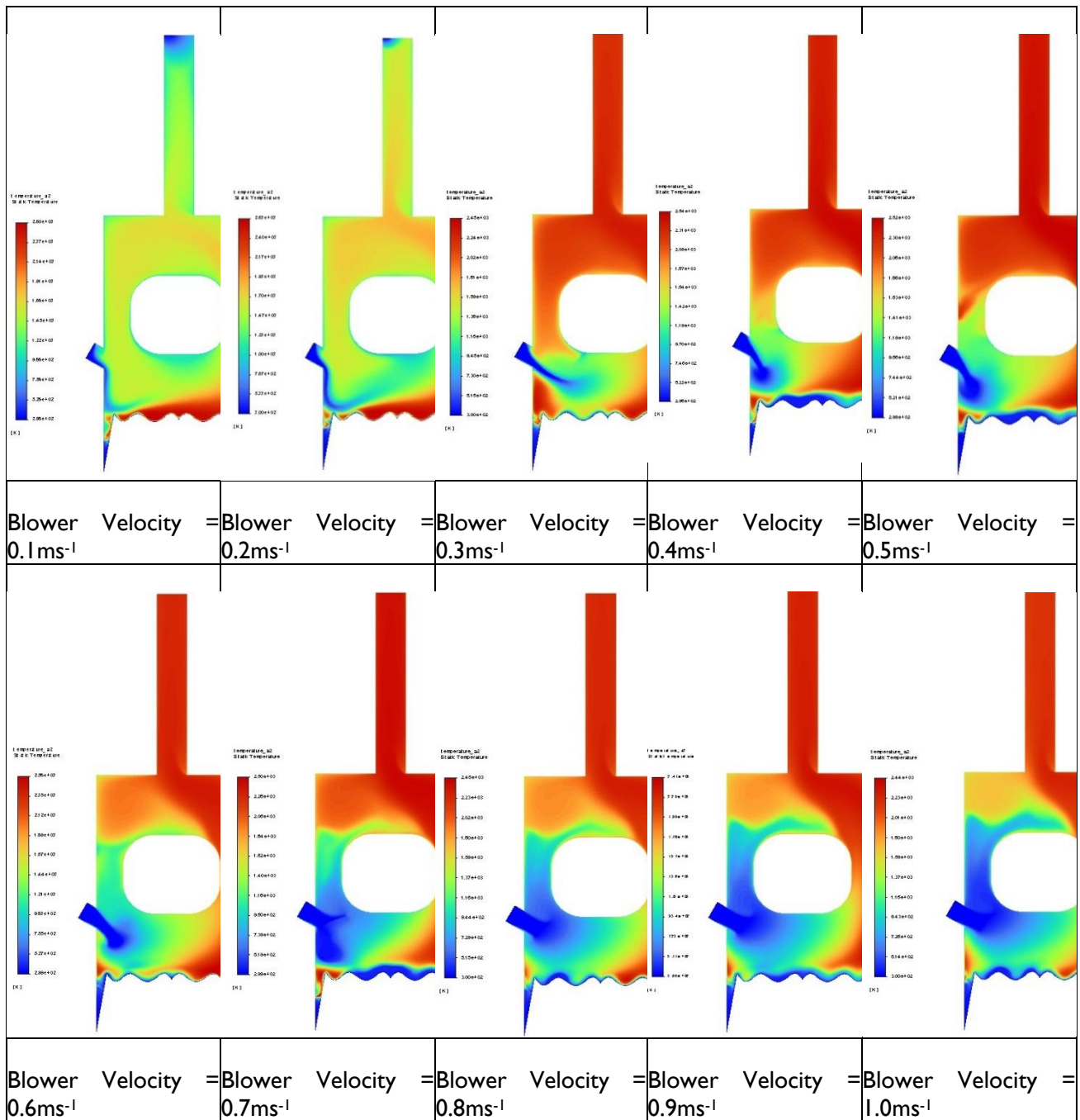


Figure 5: Simulated Temperature Contours for Sample A 2

For sample A3, Figure (6) shows that the air blower velocity of 0.1 m/s is almost insignificant in all the ANSYS generated graphs. The calorific value of the MSW yields a temperature of 1336.4K. As the air velocity is increased, so does the pattern change. The heat progresses from the entrance of the furnace, where the supplementary air is coming in contact with the fuel for the first time in the furnace. The high moisture level of 41.7%, is taken care of by the calorific value which now is 10.06 MJ/kg. The energy contained within the MSW is being used for energy generation.

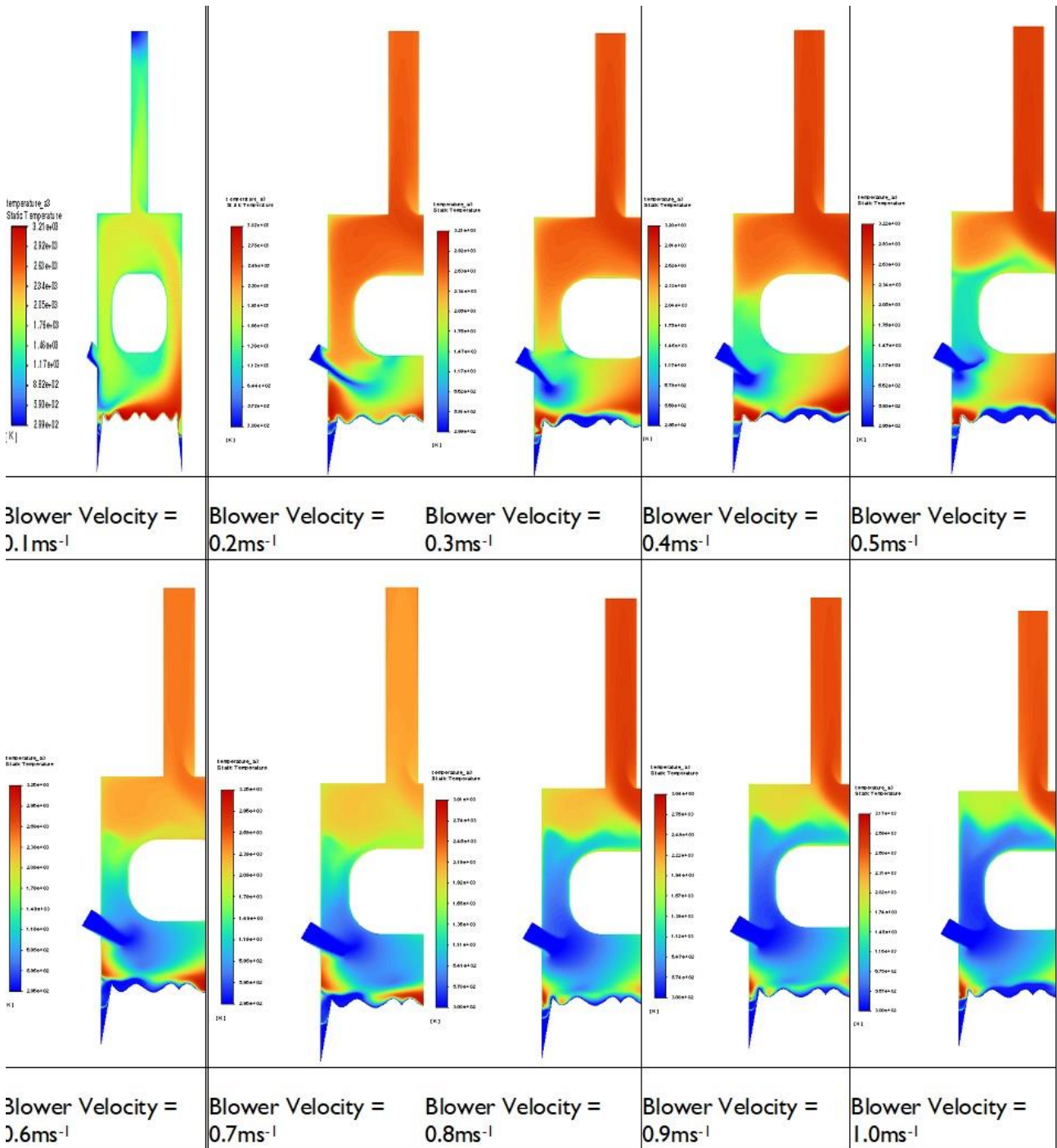


Figure 6: Simulated Temperature Contours for Sample A 3

Figure (7) shows a clear pattern on the influence of moisture on the heat content. The highest calorific value of 19.81 MJ/kg is recorded here and the moisture content of 37.49% seems even not to affect the generation in the furnace as well as the steam generation. The heat is much and is more diffused as the air blower velocity is increased. At 0.6 m/s, 0.7 m/s and 0.8 m/s, the whole boiler temperature is high and the hest envelope is more compact.

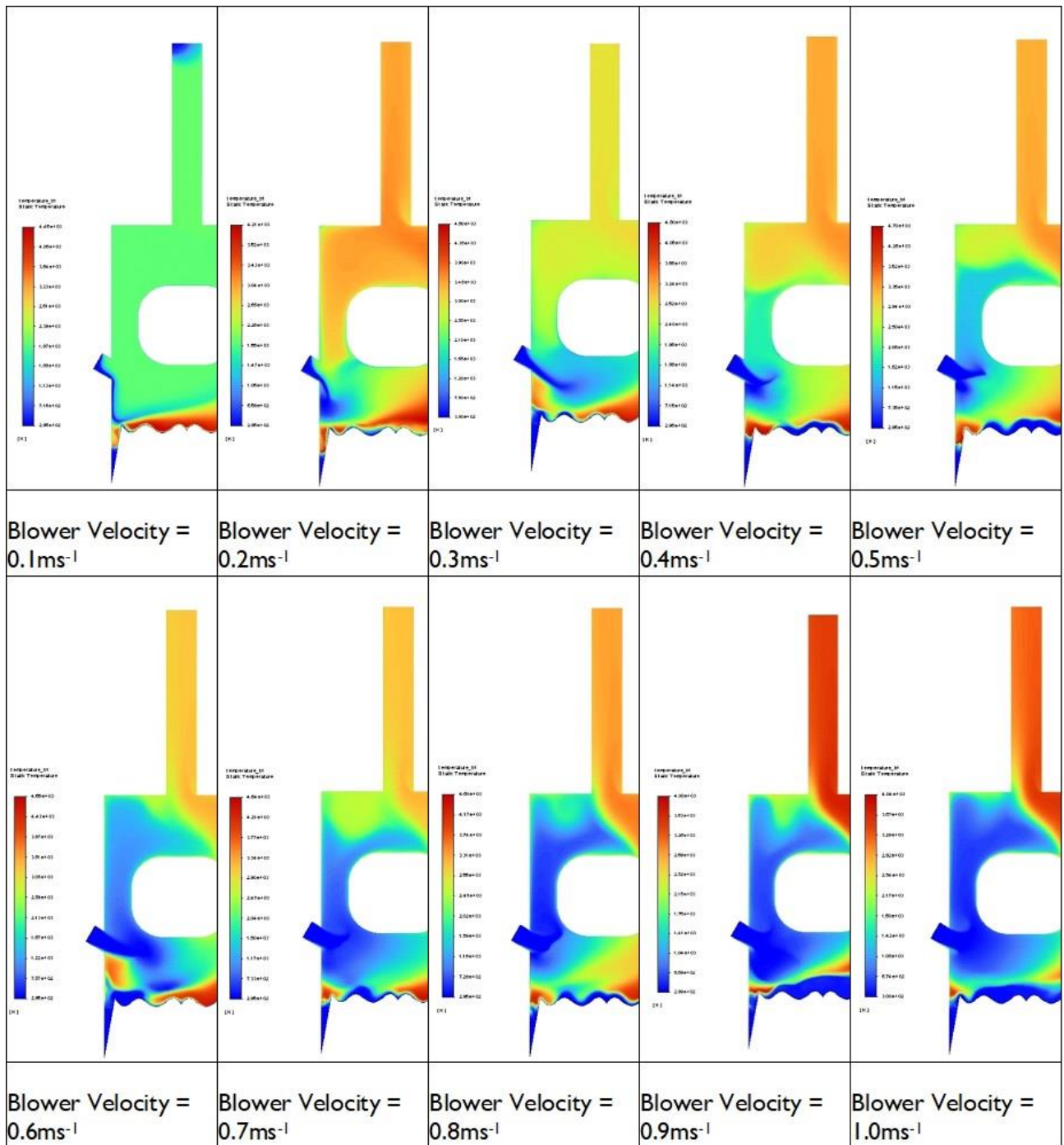


Figure 7: Simulated Temperature Contours for Sample B I

Figure (8) shows that the calorific value of 15.05 MJ/kg of the MSW yields a temperature of 1893.6K. Similarly, with the control of the blower velocity, the pattern on the graphs does not change much, at 0.6m/s up to 1.0 m/s. The heat is concentrated from the entrance of the furnace, where the supplementary air is coming in contact with the fuel for the first time in the furnace. As time increases and air blower velocity increases, so does the pattern on the ANSYS generated graphs. This is due to the high moisture level of 42.66%. However, the heat generated is high despite the fact that the moisture is high. This behaviour is similar to the previously observed one in Sample B I. The energy contained within the MSW is used to drive away the moisture but does not affect its potential of usage for other purposes.

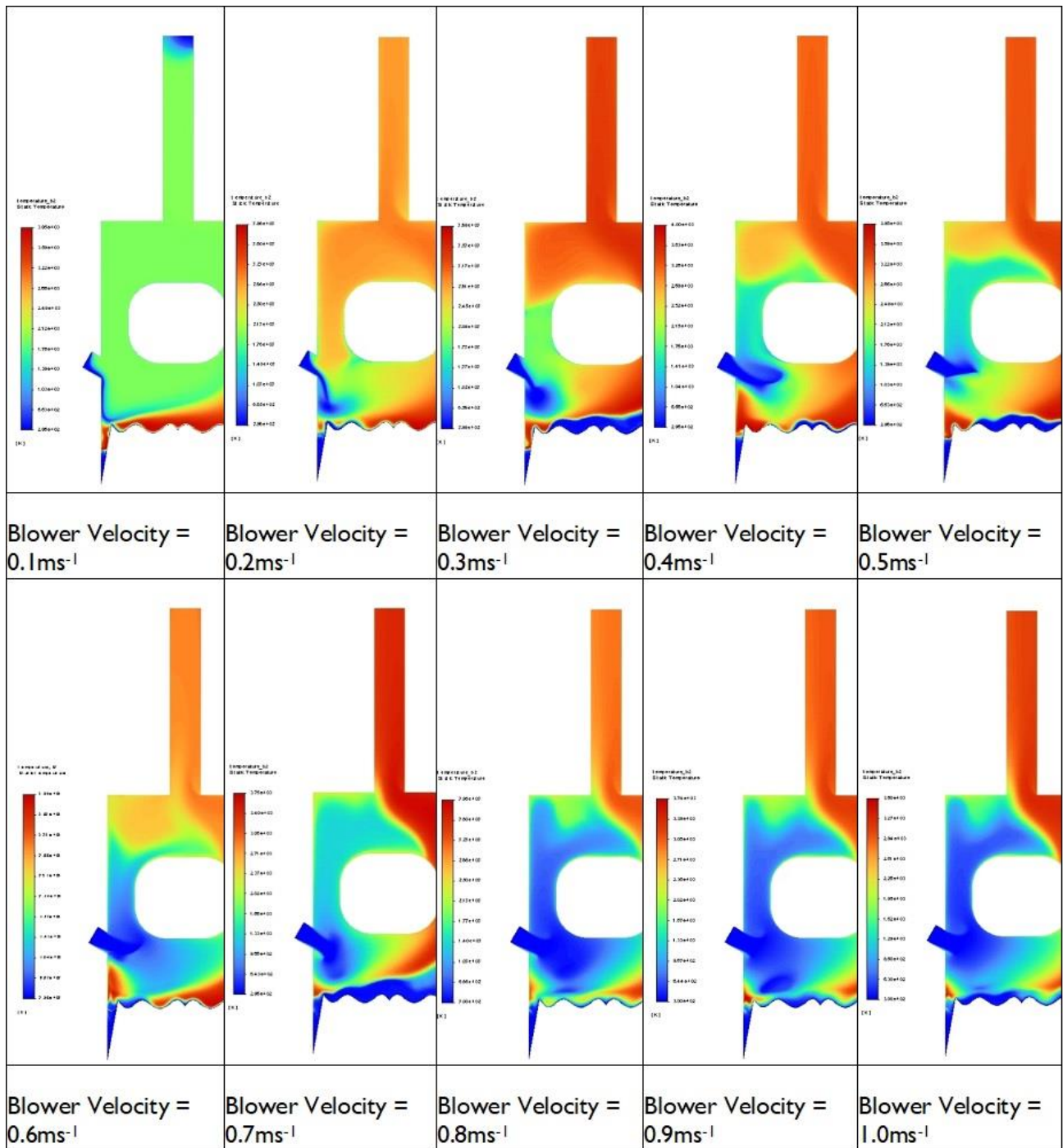


Figure 8: Simulated Temperature Contours for Sample B 2

A similar behavior and pattern to A1 figure (4) is observed in B3 Figure (9). The calorific value of the MSW yields a temperature of 1425.1 K. With the control of the air blower velocity, the pattern on the graphs changes at 0.4 m/s. The heat is concentrated in the furnace, but at 0.6 m/s. This is due to the high moisture level of 49.90%. This behavior could be due to the fact that some of the energy contained within the MSW is used to drive away the moisture and not used for other external uses.

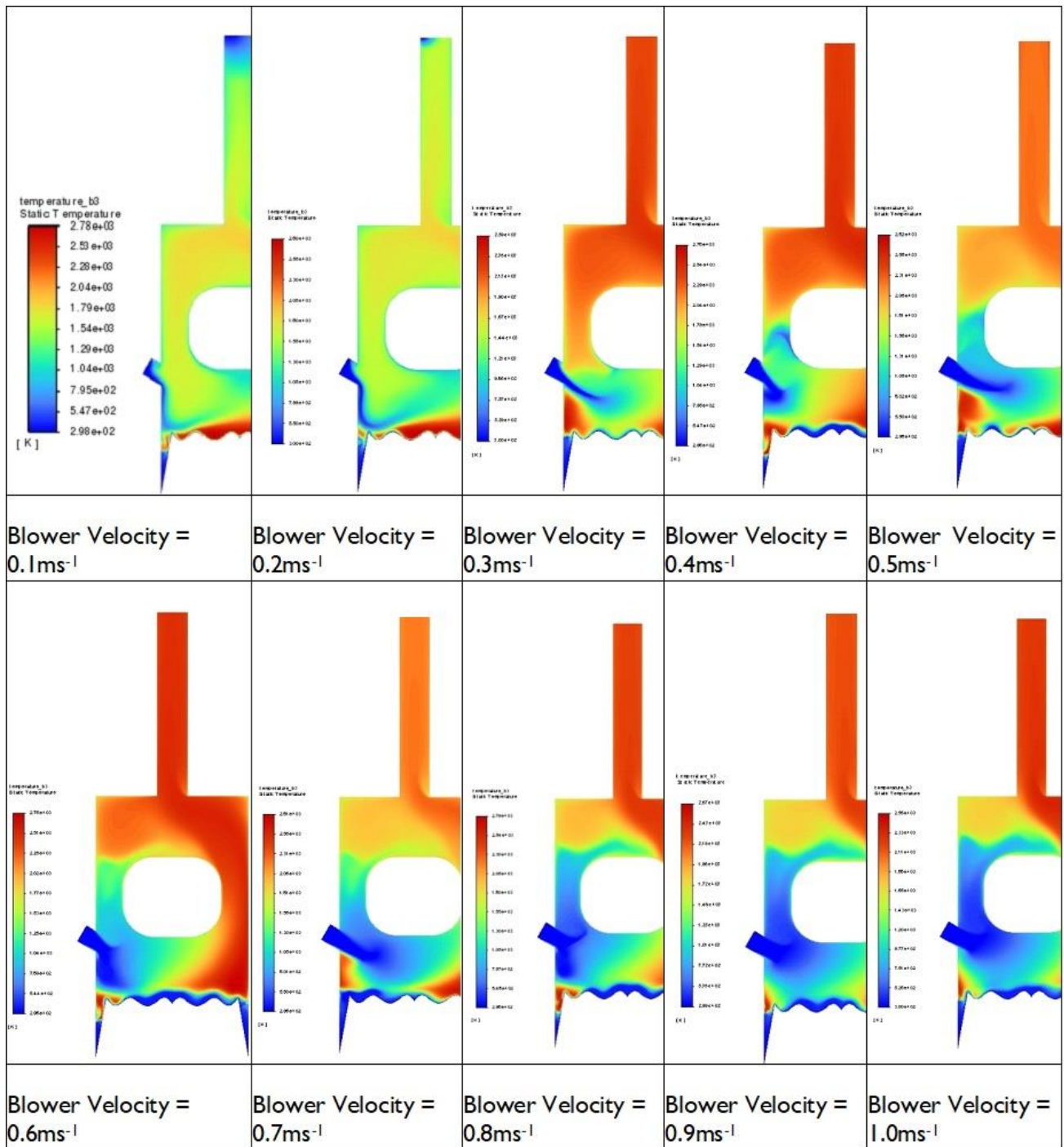


Figure 9: Simulated Temperature Contours: Sample B3

For sample C1, Figure (10) shows that the calorific value of the MSW yields a temperature of 1414.1K. The controlled air blower velocity starts becoming prominent at values of 0.4 to 0.5 m/s, but the pattern on the graphs does not change much. The heat, as previously seen, is concentrated at the entrance of the furnace, where the supplementary air is coming in contact with the fuel for the first time in the furnace. Here too, this is due to the high moisture level of 38.15%. and the behavior could be due to the fact that some of the energy contained within the MSW is used to drive away the moisture, but could be used for other external uses, to a certain extent.

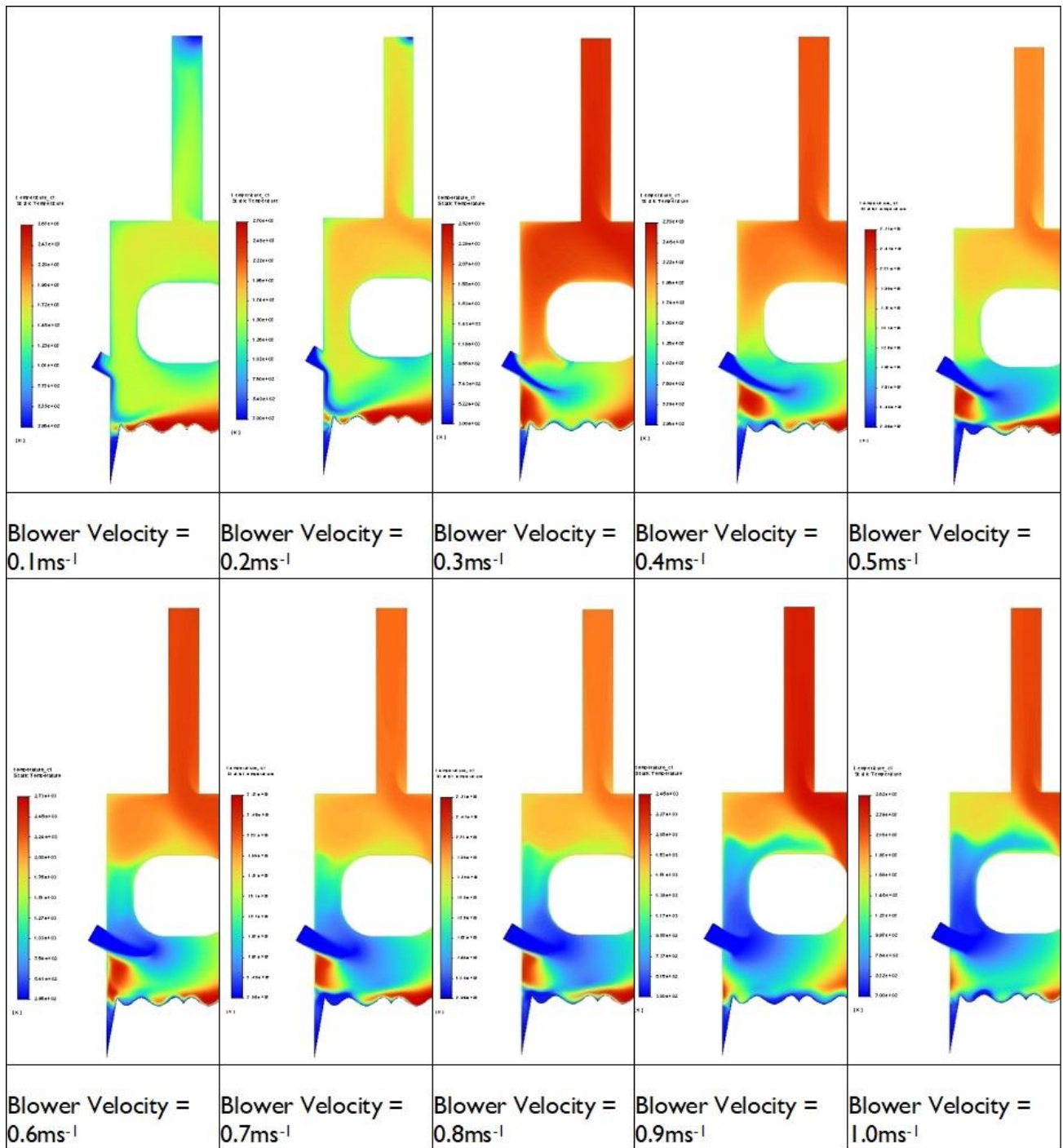


Figure 10: Simulated Temperature Contours: Sample C I

For sample C2, Figure (11) shows that the calorific value of the MSW yields a temperature of 1548.8K. With the controlled air blower velocity, the pattern on the graphs changes, uniformly at 0.2 m/s to 0.6 m/s, while the impact is felt much at 0.6m/s to 1.0 m/s. As time increase and air blower increase, so does the pattern on the ANSYS generated graphs. This could also be attributed to the high moisture level of 48.78%. This behaviour causes some of the energy contained within the MSW to drive away the moisture and not used much for other external uses like electricity generation.

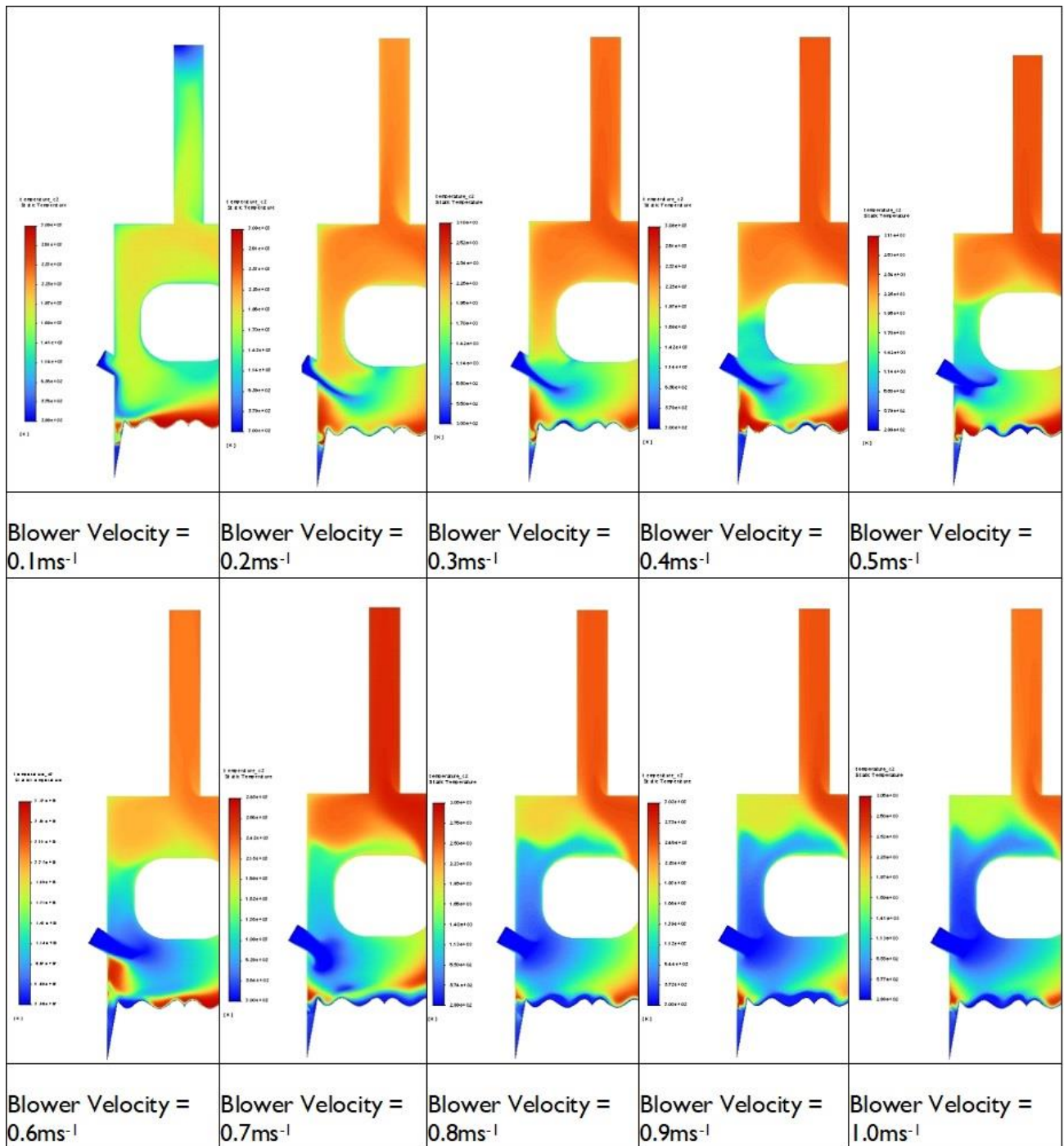


Figure 11: Simulated Temperature Contours for Sample C 2

As previously observed, Figure (12) shows a similar pattern to those of other samples. As the calorific value is low (i.e. 4.50 MJ/kg), so is the temperature, but a much higher moisture content which needs to be driven away before obtaining a useful heat. A temperature of 1036K was recorded for a moisture content of 42.58% as against a temperature of 39.24% for a temperature of 1090.7K.

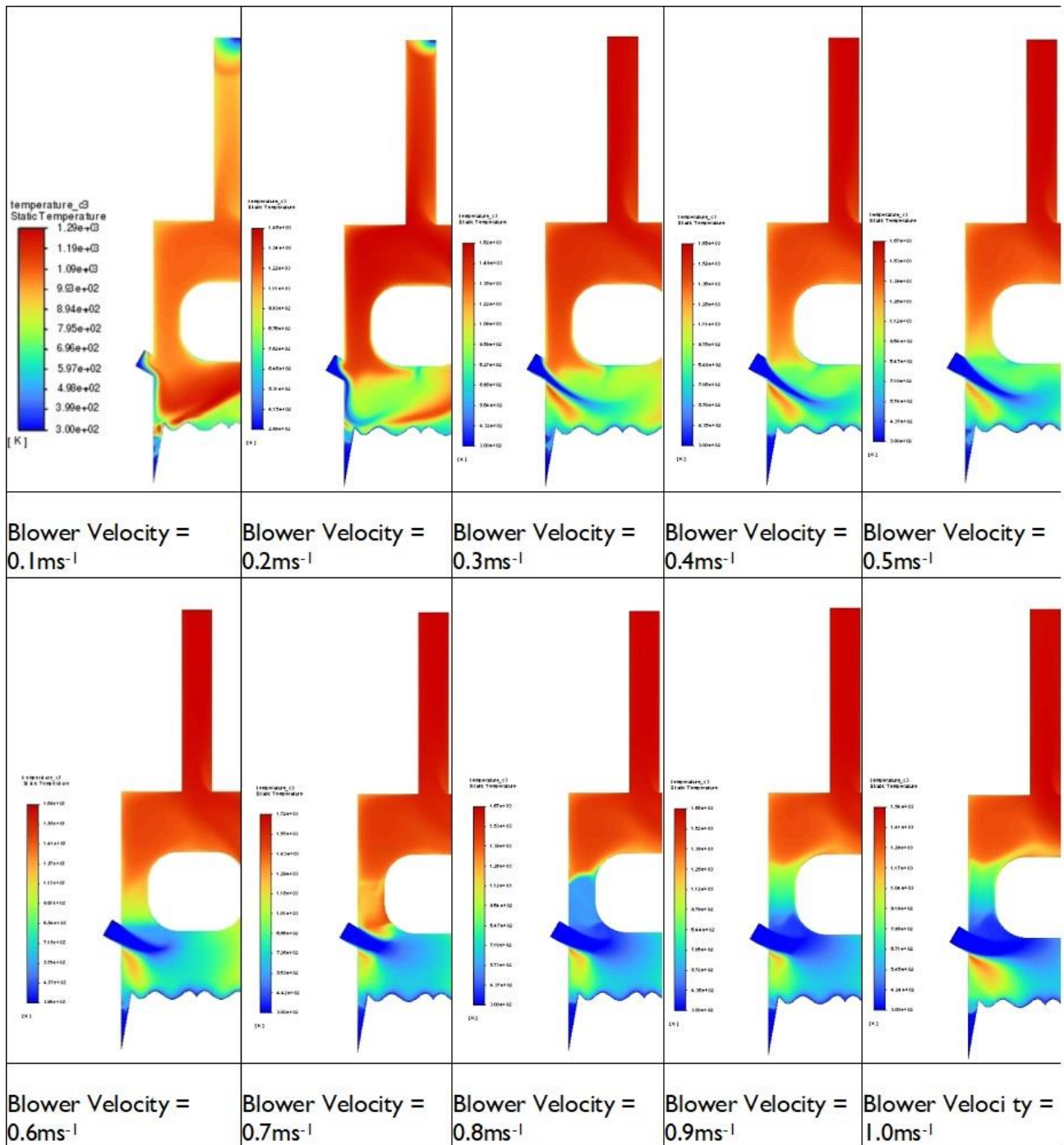


Figure 12: Simulated Temperature Contours of Sample C 3

The maximum critical velocity within the incinerator is ranging between 0.6 – 0.8 m/s. Velocity has a minimum value at the top of the boiler. There is a vortex type movement occurring close to the boiler. Smaller values of velocities could be observed, and these are due to some changes in experimental conditions or errors. This study has shown that the efficiency of energy recovery does not only depend on the design and construction of equipment, but it is also highly affected by the operation. Primary air temperature is a key parameter for incinerator operation (Khodabandeh *et al.*, (2016); Khuriati *et al.*, (2017)), but there is still limited information about how primary air temperature affects MSW incineration. As seen in Mi Yan *et al.*, (2021) who used Fluid dynamic incinerator code (FLIC) and Fluent coupled model in their study to highlight the influence of different primary air temperatures on MSW incineration in a moving grate incinerator with five zones of primary air feeding. The results too, demonstrated that as the air preheating temperature increased, so did the rate of moisture evaporation and volatile release, the latter of which could potentially lead to higher local maximum temperature in the furnace. Thus, it is possible, by using the different primary air temperature setup, to maintain a relatively high rate of moisture evaporation and total mass loss, while having a lower rate of volatile release. Ultimately, the multi-temperature primary air setup maintained a high time-averaged rate evaporation of moisture and lowers the time-averaged rate of volatile release thus, to maintain the local maximum furnace

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temperature at 1685 °C, against an average of 1482°C (1755 K) in the present study. This concept can potentially be utilized in MSW incinerators to effectively evaporate moisture from MSW while keeping the local maximum temperature in the furnace to a reasonable temperature.

This analysis shows that the high moisture levels, at low calorific values tend to reduce the potential of energy availability for other uses. But for higher calorific values like Sample B 1 and B 2, the temperatures recorded are still high and can produce steam of good quality, suitable for electricity generation. For lower values of the calorific values obtained, some of the heat released is used to drive away the moisture contained in the MSW sample.

Using the Ultimate Analyses (i.e. C, H, O, N and S) of all the samples, a regression analysis (Table 4) can be carried out in order to predict the calorific values (CFV) of the samples.

The regression equation (16) is thus:

$$CFV = 1589694 C - 35667336 H - 642103 O - 3380854 N + 78152084 S \quad (16)$$

Table 4: Regression Analysis with Coefficients

Predictor	Coef	SE Coef	T	P
No. constant				
C	1589694	787122	2.02	0.114
H	-35667336	20224514	-1.76	0.153
O	-642103	637839	-1.01	0.371
N	-3380854	2161353	-1.56	0.193
S	78152084	98022615	0.80	0.470

$$S = 4909761$$

The analysis of variance (Table 5) yields:

Table 5: Analysis of Variance

Source	DF	SS	MS	F	P
Regression	5	8.72799E+14	1.74560E+14	7.24	0.039
Residual Error	4	9.64230E+13	2.41058E+13		
Total	9	9.69222E+14			

where CFV stand for Calorific Value

To validate the developed model equation (16), there is need to compare the values obtained with the experimental values obtained using the bomb calorimeter with those from the well-established and widely used formula for biomass, like the Dulong Berthelot's (Equation 17) (Ogunsola *et al.*, 2018).

$$GCV = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1ASH \left(\frac{kJ}{kg} \right) \quad (17)$$

Table (6) shows a comparison and validation of the calorific values generated from the Model, the experiments and Dulong Berthelot's formula.

Table 6: Comparison and Validation of Experimental, Developed Model and Existing Formula

Sample ID	C	H	O	N	S	Experimental MJ/kg	Present Study MJ/kg	Dulong Formula MJ/kg
Sample A1	46.22	0.21	41.85	11.64	0.08	4.3110	6.01	6.21
Sample A2	44.87	0.24	43.94	10.83	0.12	7.0610	7.31	9.30
Sample A3	43.14	0.20	47.09	9.46	0.11	10.0612	7.82	8.53
Sample B1	47.91	0.23	41.42	10.34	0.10	19.8107	14.21	7.76
Sample B2	48.02	0.19	41.25	10.45	0.09	15.0559	14.77	6.99
Sample B3	47.08	0.20	42.15	10.50	0.07	5.7262	10.61	5.44
Sample C1	45.90	0.55	47.07	6.35	0.13	7.5077	11.81	10.08
Sample C2	46.10	0.67	46.70	6.44	0.09	8.4217	4.66	6.99
Sample C3	46.40	0.76	45.93	6.77	0.14	4.5086	5.21	10.85

The Bomb calorimeter yielded a value 82.55 MJ/Kg with an average of 9.17 MJ/kg, while the Model generated formula yielded 82.41 MJ/kg and an average of 9.15 MJ/kg. The Dulong Berthelot formula in turn, yielded 72.15 MJ/kg with an average of 8.01 MJ/kg. The bomb calorimeter and Model generated calorific values are in very good agreement of up to 98%. Those values also compare favorably, for up to 87.5% with the Model, and 87.40% when compared to the Dulong Berthelot's with discrepancies in individual samples when the samples are considered. These discrepancies can be due to the fact that the Ash content is not captured in the formula.

3.1 Results of Experimental Analyses

In order to generate experimental data, a physical batch type model of the MSW incinerator was designed (scale 1:10) and constructed (Plates 1), and tested using locally available materials; for the evaluation of boiler temperature, steam pressure within the boiler, the steam pressure at nozzle exit/turbine entrance and the electricity voltage (V). This physical model is based on the principle of dynamic similarities (Bansal, (2005); Cengel and Cimbala, (2010)) where sizes could be reduced, keeping the characteristics constant, like temperature and pressure in this case. For the experiments, a scale of 1:5 is considered and the internal sizes are: 0.2 m x 0.2m x 0.4 m yielding a volume of 0.016 m³. Thus, the maximum allowable MSW volume per loading could be taken as 5 kg, considering a 0.2 m height of the MSW bed.

To ensure a thorough composition, the average of seasons was taken. Tables (7 to 9) show the experimental results.



Plate 1: Front View of the Constructed Batch MSW Incinerator

Table 7: Experimental Results for Sample A

Furnace Temperature (K)	Boiler Temperature (K)	Steam Pressure at Boiler (Bar)	Steam Pressure at Nozzle (Bar)	Generated Voltage (Volts)
1029.4	971.7	2.6	2.7	2
1116.6	1041.6	3.2	3.4	2.5
1259.8	1173.8	4.1	4.2	2.8
1472.6	1273.3	4.8	4.9	3.2
1518.6	1393.6	5.2	5.4	3.4
1594.4	1418.5	5.7	5.8	4
1641.9	1373.2	6.1	6.2	4.4
1440.3	1343.1	6.8	7	5
1397.1	1303.4	7.1	7.3	5.7
1379.2	1285.8	7.8	8.1	6.4

Table 8: Experimental Results for Sample B

Furnace Temperature (K)	Boiler Temperature (K)	Steam pressure at Boiler (Bar)	Steam pressure at Nozzle (Bar)	Generated Voltage (Volts)
1321.4	1216.1	2.8	2.9	2.7
1564.7	1489.6	3.6	3.8	3
1786.8	1577	4.3	4.4	3.6
1865.9	1619.2	5.1	5.1	3.8
1896.3	1640.2	5.8	5.9	4
1865.4	1645	6.2	6.4	4.7
1856.7	1623.6	6.8	6.9	5.1
1883.5	1635.9	7.4	7.5	5.8
1711.2	1595.7	8.1	8.3	6.4
1689.9	1532.7	8.8	8.9	6.6

Table 9: Experimental Results for Sample C

Furnace Temperature (K)	Boiler Temperature (K)	Steam pressure at Boiler (Bar)	Steam pressure at Nozzle (Bar)	Generated Voltage (Volts)
1029.4	1244.7	3.2	3.4	2.7
1116.6	1314.6	3.8	4	3.8
1259.8	1446.8	4.7	4.8	4
1472.6	1546.3	5.4	5.6	4.2
1518.6	1666.6	6.2	6.4	4.6
1594.4	1691.5	6.8	7	5.5
1641.9	1646.2	7.1	7.3	5.6
1440.3	1616.1	7.7	7.8	5.8
1397.1	1576.4	8.3	8.4	6.4
1379.2	1558.8	8.7	8.8	6.5

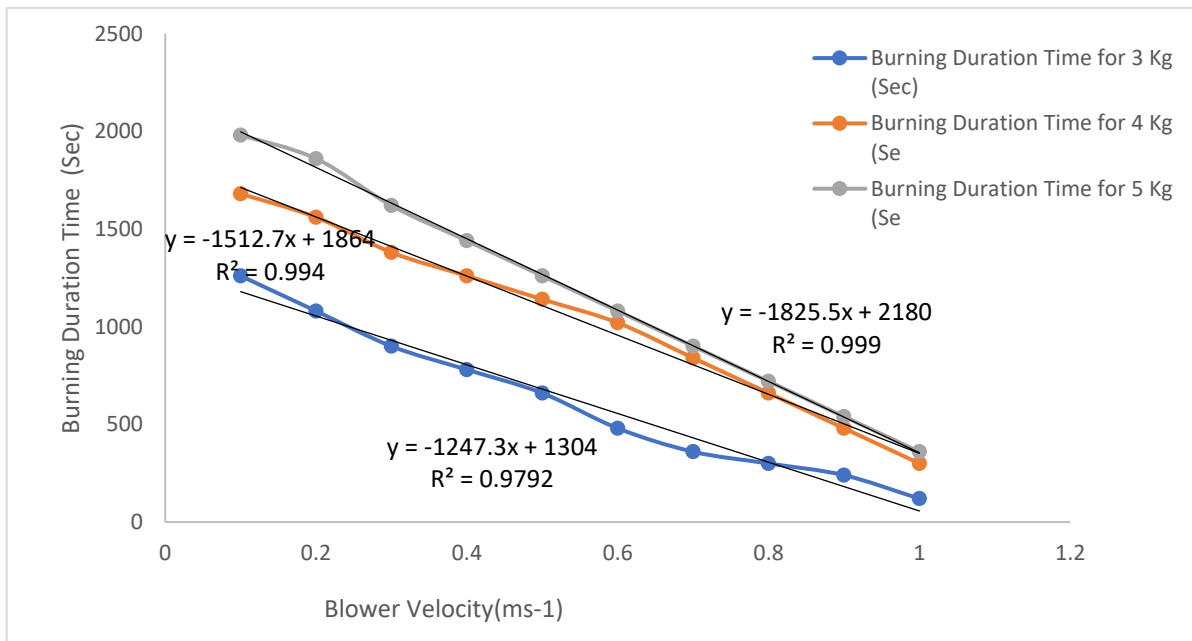


Figure 13: Graph of Blower Velocity and Burning Time for Various Feed Rates of Sample A

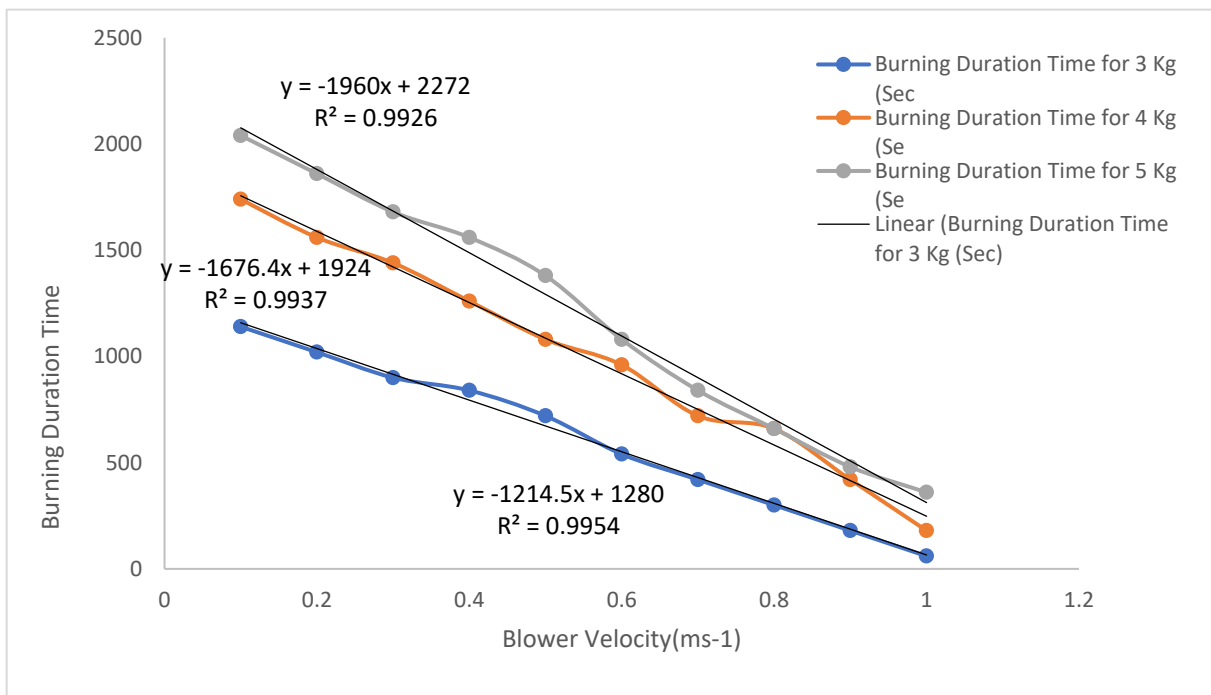


Figure 14: Graph of Blower Velocity and Burning Time for Various Feed Rates of Sample B

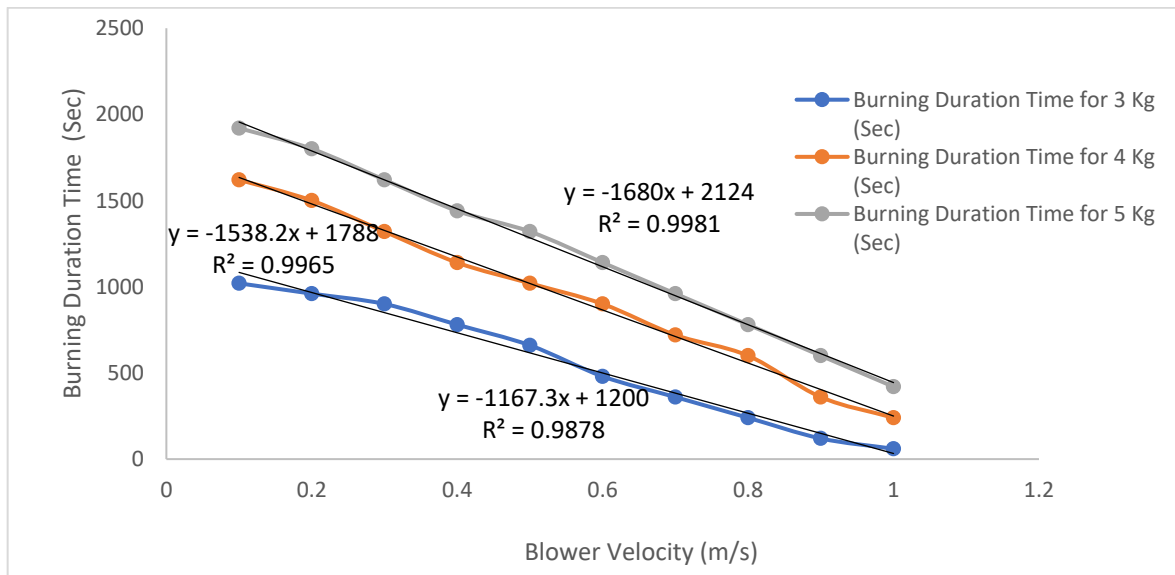


Figure 15: Graph of Blower Velocity and Burning Time for Various Feed Rates of Sample C

A comparison of the simulated results and experimental results showed that while Sample A had 1090. K, 1409.9 K and 1609.6 K, Sample B had 1918.1 K, 1893.6 K and 1425.1 K, Sample C had 1413.1 K, 1548.8 K and 1036.6 K during simulation against an average of 1641.9 K; 6.4 Volts produced at 1379.2 K for sample A, an average of 1896.3 K; 6.6 Volts produced at 1689.9 K and lastly for sample C, an average of 1641.9 K; 6.5 Volts at 1379.2 K, during the experiments using the batch MSW incinerator. Figures (13), (14) and (15) exhibit a similar linear pattern, showing an increase in the time of incineration of the MSW, as the feed's quantity is raised. This assessment is supported by the R^2 values of 0.979 for 5 kg load, 0.994 for 4 kg load and 0.999 for 3 kg load, for sample A. For sample B, the R^2 values range from: 0.992, 0.993 and 0.995 for 5 kg, 4 kg and 3 kg respectively. For sample C, the R^2 values range from: 0.998 for 5 kg, 0.996 for 4 kg and 0.987 for 3 kg. This shows that the moisture content, the feed rate and the energy content of the MSW greatly affect the quantity of electricity generated from the municipal solid wastes of Maiduguri, with the samples from University of Maiduguri, yielding lower electricity than the remaining locations. The MSW samples in Area C yield 7,500 MJ/kg, 8,420 MJ/kg and 4,500 MJ/kg, with an average of 6,800 MJ/kg, which is lower than the average minimum calorific value of 7000 MJ/kg, required for setting up an incineration plant with energy recovery (Olisa and Ajoko, 2018; Yeganeh et al., 2023). This implies the need to add a supplementary fuel to the MSW, in Area C.

4. Conclusion

At the end of this research work, the following conclusions were drawn:

1. Tests ran yielded results which are in good agreement with the simulated results. The developed and validated mathematical model has predicted optimum temperatures as 1370 K as against an experimental value of 1379.2 K for samples in Area A, 1745.6 K against an experimental value of 1689.9 K for samples in Area B, and 1332.63 K against 1379.2 K obtained experimentally from samples in Area C.
2. The simulated moisture content, feed rate and energy content using ANSYS revealed that critical air velocity of 0.6m/s to 0.8 m/s affect the pressure and temperature which are other important design parameters associated to MSW power plant.
3. The waste feed rate, moisture content, calorific value, have a huge impact on the ability of MSW to generate electricity, for a longer time as the feed rate is raised, while the moisture content gets reduced.
4. A mathematical equation for the calorific value was developed using ANSYS, Ms Excel and was found to compare favourably, for up to 87.5% agreement with the Model, and 87.40% agreement when compared to the Dulong Berthelot's formula.

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