COMPUTATIONAL FLUID DYNAMICS CALCULATIONS OF WASTE-TO-ENERGY PLANT COMBUSTION CHARACTERISTICS

by

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The combustion process for using municipal solid waste as a fuel within a waste to energy plant calls for a detailed understanding of the following phenomena. Firstly, this process depends on many input parameters such as proximate and ultimate analyses, the season of the year, primary and secondary inlet air velocities and, secondly, on output parameters such as the temperatures or mass fraction of the combustible products. The variability and mutual dependence of these parameters can be difficult to manage in practice. Another problem is how these parameters can be tuned to achieving optimal combustible conditions with minimal pollutant emissions, during the plant-design phase. In order to meet these goals, a waste-to-energy plant with bed combustion was investigated by using computational fluid-dynamics approach. The adequate variable input boundary conditions based on the real measurement are used and the whole computational work is updated using real plant geometry and the appropriate turbulence, combustion, or heat transfer models. The operating parameters were optimized on output parameters through a trade-off study. The different operating conditions were varied and the combustible products were predicted and visualized. Finally, the response charts and matrix among the input and output parameters during the optimization process are presented, which monitored the dependence among these parameters.

Key words: municipal solid waste, bed combustion, computational fluid dynamics, numerical optimization, goal driven optimization, trade-off study, parameters correlation

Introduction

Nowadays, bed-combustion on a grate is the most common way to burn municipal solid waste (MSW) in waste to energy plants (WTEP). The combustion in these plants is very specific due to the characteristics of fuel (MSW), which depends on the waste's composition, such as proximate and ultimate analyses, season of the year, primary and secondary inlet air velocities and many other parameters which constantly change in some frames. The goals concern how to harmonize the optimal combustible conditions using minimal pollutant

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emissions, during the WTEP project phase. In order to meet these goals, WTEP with bedcombustion was numerically investigated by using the computational fluid dynamics (CFD) approach [1-13], by the non-stationary calculation of the ANSYS CFX 12.0 code in a WORKBENCH 2 environment. By using this complex numerical tool, the input and output parameters were followed and their mutual interaction visualized. Mathematical models for boundary-condition predictions were developed, such as FLIC [6, 8-11] and the TAMARA [3] test project to find out combustible products distribution within the gaseous phase above the fuel bed and along the moving grate. The combustion of MSW during the gaseous combustion phase has many phases such as moisture evaporation, waste devolatilisation, combustion of volatiles, mixing and fixed carbon combustion during heterogeneous chemical reactions [10]. So the input boundary conditions have to be harmonized using these phenomena. Some optimization methods are described in literature [5, 14, 15], but these work do not discuss the interaction among the parameters, as used here.

Models description

The combustion in a WTEP is described quite accurately by a system of differential equations regarding reactive flow, the so called Reynolds averaged Navier-Stokes equations (RANS), as presented in the following form:

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial}{\partial x_j} \ \overline{\rho} \overline{\upsilon}_j = 0 \tag{1}$$

$$\frac{\partial}{\partial t} \ \overline{\rho}\overline{\nu}_{j} + \frac{\partial}{\partial x_{j}} (\overline{\rho}\overline{\nu}_{j}\overline{\nu}_{i}) = -\frac{\partial p}{\partial x_{i}} + \overline{f_{ni}} - \frac{\partial}{\partial x_{j}} (\overline{\tau}_{ij} + \overline{\rho}\overline{\nu}_{j}'\overline{\nu}_{i}')$$
(2)

$$\frac{\partial}{\partial t} (\overline{\rho}\overline{h}) + \frac{\partial}{\partial x_j} (\overline{\rho}\overline{\nu}_j\overline{h}) - \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j} (\overline{q}_j + \overline{\rho}\overline{\nu'_j}\overline{h'}) = \overline{I_T} + \overline{I_R}$$
(3)

Reynolds' stresses $\overline{\rho \upsilon'_i \upsilon'_i}$ are modelled by the introduction of turbulent viscosity η_i .

$$\overline{\rho \upsilon_j' \upsilon_i'} = \frac{2}{3} \delta_{ij} \left(\rho k + \eta_t \frac{\partial \upsilon_k}{\partial x_k} \right) - \eta_t \left(\frac{\partial \upsilon_i}{\partial x_j} + \frac{\partial \upsilon_j}{\partial x_i} \right)$$
(4)

Turbulent viscosity can be determined using various turbulent models to close-down the system of Reynolds' equations. The two-equation $k-\tilde{z}$ turbulent model is used for the purpose of the presented reactive flow modelling. The application of $k-\tilde{z}$ turbulent model in the modelling of reactive-flows has already been proven by many authors as very successful. Turbulent viscosity is computed using:

$$\eta_t = \rho C_\eta \frac{k^2}{\varepsilon} \tag{5}$$

where k is the turbulent kinetic energy $-k = 0.5(\overline{\nu'_i \nu'_i})$ and ε its dissipation (irreversible transformation of kinetic energy into internal energy).

Local values of k and ε are computed using the following transport equations:

$$\frac{\partial}{\partial t} \rho k + \frac{\partial}{\partial x_j} \overline{\upsilon}_j k - \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] = I_k$$
(6)

$$\frac{\partial}{\partial t} \rho \varepsilon + \frac{\partial}{\partial x_j} \overline{\upsilon}_j \varepsilon - \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_i}{\sigma_{\varepsilon}} \right) \frac{\partial \varepsilon}{\partial x_j} \right] = I_{\varepsilon}$$
(7)

the source terms are modelled as:

$$I_{k} = \eta_{t} \left(\frac{\partial \overline{\nu}_{i}}{\partial x_{j}} + \frac{\partial \overline{\nu}_{j}}{\partial x_{i}} \right) \frac{\partial \overline{\nu}_{i}}{\partial x_{j}} - \rho \varepsilon$$
(8)

$$I_{\varepsilon} = C_1 \frac{\varepsilon}{k} \left[\eta_t \left(\frac{\partial \overline{\upsilon}_i}{\partial x_j} + \frac{\partial \overline{\upsilon}_j}{\partial x_i} \right) \frac{\partial \overline{\upsilon}_i}{\partial x_j} \right] - C_2 \rho \frac{\varepsilon^2}{k}$$
(9)

Reynolds' enthalpy flux $\overline{\rho v'_j h'}$ in eq. (3) is also defined with turbulent viscosity:

$$\overline{\rho \upsilon'_j h'} = -\frac{\eta_t}{\Pr_t} c_p \frac{\partial T}{\partial x_j}$$
(10)

where Pr_t is the turbulent Prandtl number. C_{η} , C_1 , C_2 , σ_k and σ_{ε} are constants, and their values used in the presented work are: $C_{\eta} = 0.09$; $C_1 = 1.44$; $C_2 = 1.92$; $\sigma_k = 1$, and $\sigma_{\varepsilon} = 1.3$.

Advection – diffusive equation of mass species (ξ_k) of the component k has due to Reynolds' averaging, an additional term called turbulent mass species flux:

$$\overline{\rho \xi_k' \upsilon_j'} = \frac{\eta_t}{\operatorname{Sc}_t} \frac{\partial \xi_k}{\partial x_j}$$
(11)

and can be modelled with turbulent viscosity using the k- ε model. The complete advection – diffusive mass species equation is:

$$\frac{\partial}{\partial t} \overline{\rho \xi_k} + \frac{\partial}{\partial x_j} \overline{\rho \upsilon_j \xi_k} - \frac{\partial}{\partial x_j} \left[\left(\overline{\rho D_k} + \frac{\eta_t}{\mathrm{Sc}_t} \right) \frac{\partial \xi_k}{\partial x_j} \right] = \overline{I_{\xi_k}}$$
(12)

where Sc_t is the turbulent Schmidt number and D_k molecular diffusion coefficient of component k. With the new term:

$$\Gamma_{k,\text{eff}} = \rho D_k + \frac{\eta_t}{\text{Sc}_t} = \Gamma_k + \frac{\eta_t}{\text{Sc}_t}$$
(13)

the eq. (12) can be rewritten as:

$$\frac{\partial}{\partial t} \overline{\rho \xi_k} + \frac{\partial}{\partial x_j} \overline{\rho \upsilon_j \xi_k} - \frac{\partial}{\partial x_j} \left(\Gamma_{k, \text{eff}} \frac{\partial \xi_k}{\partial x_j} \right) = \overline{I_{\xi_k}}$$
(14)

Source terms of energy and mass species transport equations are computed by the following two equations where ω_k is computed by the turbulent combustion model:

$$\overline{I_T} = -\sum_{k=1}^N \Delta H^o_{f,k} \overline{\varpi}_k \tag{15}$$

$$I_{\xi_k} = M_k \overline{\omega}_k \tag{16}$$

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where $\Delta H_{f,k}^{\circ}$ is the standard heat formation and M_k the molecular mass of the component k. In eqs. (15) and (16) the ω_k stands for the formation/consumption rate of component k and is defined by the following expression:

$$\overline{\omega}_{k} = \frac{\mathrm{d} X_{k}}{\mathrm{d}t} = \nu_{k}'' - \nu_{k}' \ \overline{R}_{k}$$
(17)

which is written in following form of general chemical reaction:

$$\sum_{k=1}^{N} \nu'_{k} X_{k} \xrightarrow{k_{f}} \sum_{k=1}^{N} \nu''_{k} X_{k}, \qquad (18)$$

where ν'_k and ν''_k designate the stoichiometric coefficients of component k for reactants and products, respectively. Chemical reaction rate R_k in eq. (17) is calculated by appropriate combustion models. It has to be pointed out that nowadays several turbulent combustion models are in practical use. Their application depends on the type of combustion (diffusion, kinetic, mixed), fuel type (solid, liquid, gaseous), and combustion device (furnace, boiler, engine). Most of models include various empirical constants which need to be individually determined case by case. In this case, the eddy dissipation combustion model has been applied on the basis of Ansys best practice recommendations and its references [14, 15] for this kind of combustion.

Geometry, meshing, and boundary conditions

Using the computational fluid dynamics (CFD) approach the combustion processes can be predicted and the operating conditions with combustion chamber design can be optimized in existing WTEP or during the project phase of the new one. Figure 1 shows the 2-D engineering plan view of WTEP. The WTEP was built on this basis and operates with refuse derived fuel (RDF) as a fuel produced with mechanical biological treatment (MBT) from MSW.

Figure 2 shows the grate details in the primary combustion chamber with waste input and fig. 3 shows the secondary combustion chamber with secondary and tertiary air inlets. Moreover, the exit of the secondary combustion chamber can be also seen.





Figure 2. Grate in primary combustion chamber



Figure 3. Secondary and tertiary air inlets in secondary combustion chamber

The 3-D geometry plan on the basis of engineering plans in real measurements was drawn using a Design Modeler packet (fig. 4) which is also included within the Ansys Workbench environment. Each dimension is marked on the plan with corresponding input dimensions which can be varied. In this way each dimension is easy and quickly modified and the entire construction can be modified and redrawn, and further steps, such as like mesh creation or design optimization are possible in real time.

On this basis, the mesh of 160,871 nodes and 810,978 elements (fig. 5) is created. It is very important that the mesh creation is designed optimally which means that the mesh has more density in significant areas such as air-input or when the combustion processes are very intensive, such as in the primary and secondary combustion chambers. Due to these facts, an optimal control-volume size is needed and the remeshing iteration process is established to achieve the optimum mesh creation. This means that a smaller control volume is applied where the combustion process is more intensive or at the reactant's inlet in the WTEP, which is clearly seen in fig. 5. Now, the mesh is prepared for another step.





Figure 4. 3-D geometry plan of WTEP with dimensions

Figure 5. WTEP meshing in 3-D view

In addition, boundary conditions with entire combustion, radiation, particle tracking, and other models with input and output parameters are set up and the solver starts to reach the convergence criteria, such as the maximum number of iterations or the residual target. These input parameters have a operating conditions such as intake velocities, temperatures, reactants mass fraction (MFR), dimension values, and output parameters such as temperatures, combustion products MFR, and other exhaust parameters. It is well-known that the concentrations of gaseous components which are created from MSW combustion, such as carbon monoxide, methane, hydrogen, nitric oxide or oxygen, above the fuel bed, are differently distributed along the grate set. These facts are taken into consideration when defining the boundary conditions. Figure 6 shows the different MFR's of gaseous components created from MSW, including the temperature along the co-ordinate x (along the grate). These components are changeable and dependent on the distance of co-ordinate x. In this paper, the boundary conditions are set as a polynomial function of variable *x*:

$$f_i(x) = a_i x^3 + b_i x^2 + c_i x + d_i, \quad i = 1... n; a, b, c, d = constants$$
 (19)

corresponding to the statistics of the local measurements of specific gaseous components along the grate [3, 5, 7, 8, 10].



Figure 6. Boundary conditions in the direction x coordinate for different input parameters

Figure 7 shows the marked areas for primary, secondary and tertiary air inlets, the fuel inlet and flue gases outlet. In addition, a special cross-section for the secondary combustion chamber at the inlet (SecIn) and outlet (SecOut) were created to identify and to

monitor the combustion products and other parameters in this significant area. In this way, the location of a single parameter can be distinguishable.

In this study, the measured operating parameters from existing WTEP are used as the input parameters (IP). In addition, the reactions for gaseous combustion are also defined and the entire model is solved. Several other authors have used the FLUENT solver code [3, 5-12] but, in this study, the CFX V12.0 solver code in the Workbench 2 environment, which was developed by Ansys, Inc., was applied. These two solver codes now operate within the Workbench 2 environment by the same firm so we cannot expect any major differences by using one of the codes. Table 1 shows the main settings review, as applied in the CFD simulation.

Results and discussion

In this study three input parameters (IP) were used: secondary air inlet velocity (P1 – InSecAirVelocity), MSW velocity (P2 – MSWVelocity), and oxygen MFR (P3 – MassInVelocity, dimensionless) and many other output parameters (OP). The complete parameters review is shown in tab. 2.



Figure 7. Area definition in WTEP

Submodel/phenomenon	Type/approach
Turbulence model	k-ε
Combustion model	Eddy dissipation
Thermal radiation model	P1
Spectral model	Gray
Heat-transfer model	Fluid dependent
Fluid pair: methane air mixture MSW ash	Particle coupling = Fully coupled
Interphase heat transfer	Ranz Marshall
Interphase thermal radiation	Opaque emissivity = 1
Momentum transfer: drag force	Schiller Naumann

Table 1. Applied main settings review

The optimization process was carried out using design exploration which is a powerful tool for designing and understanding the analyses response of parts and assemblies. It is a deterministic method based on the design of experiments (DOE) and various optimization methods with parameters as their fundamental components. DOE techniques have one common characteristic: they try to locate the sampling points such that the space for random input parameters is explored in the most efficient way, or to obtain the required information with a minimum of sampling points.

Sample points (fig. 8) in efficient locations will not only reduce the required number of sampling points, but also increase the accuracy of the response surface derived from the results of the sampling points. By default the deterministic method uses a central composite design, which combines one centre point, points along the axes of the input parameters, and the points determined by a fractional factorial design. Using these three input parameters, fifteen different design points were created and the results for output parameters calculated, as which is shown graphically in fig. 8.

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Parameter number	Parameter mark	Parameter type	Parameter description	Unit
P1	InSecAirVelocity2	Input	Secondary air inlet velocity	$[ms^{-1}]$
P2	MSWVelocity	Input	Minicipal solid waste velocity – gasefied phase	[ms ⁻¹]
P3	MassInSecOxygen	Input	Oxygen mass fraction at secondary air inlet	[-]
P4	AshTempMax	Output	Maximal ash temperature	[K]
P5	CH4Out	Output	Methane mass fraction at outlet	[-]
P6	COOut	Output	Mass fraction of carbone monoxide at outlet	[-]
P7	COSecIn	Output	Mass fraction of carbone monoxide at secondary chamber inlet	[-]
P8	COSecOut	Output	Mass fraction of carbone monoxide at secondary chamber outlet	[-]
P9	O2Out	Output	Oxygen mass fraction at outlet	[-]
P10	TempOut	Output	Outlet temperature	[K]
P11	AshTime	Output	Ash residence time	[s]

Table 2. Input and output parameters review



Figure 8. Parameters parallel chart for 15 different sample points with input and output parameters (color image see on our web site)

On the other hand, two different output parameters: maximal ash temperature (P11) and ash residence time (P4) can also be established by design points vs. a parameter diagram (fig. 9). In this diagram the calculated parameter's values from among different design point can be presented.

Goal driven optimization (GDO) is a constrained, multi-objective optimization technique in which the best possible designs are obtained from sample sets, given the objectives you set from para-



Figure 9. Design points vs. parameter diagram

meters. GDO can be used for design optimization in three ways: the screening, the multiobjective generic algorithm (MOGA) approach, and non-linear programming by the quadratic lagrangian approach (NLPQL). The screening approach is a non-iterative direct sampling method using a quasi-random number generator based on Hammersley's algorithm. The MOGA approach is an iterative algorithm, which can optimize problems with continuous input parameters. NLPQL is a gradient-based single-objective optimizer which is based on a mathematical optimization algorithm developed by Klaus Schittkowski. GDO has several more possible objectives which are: no-objective, minimize, maximize, target value which is less or equal and grate or equal to the input target value. The importance of the parameter is default, lower, and higher.

By setting these targets, the three best candidates (A, B or C) were chosen, as they best met all the input requirements (tab. 3). Table 3 shows the setting and results of trade-off optimization using IP and OP. As can be seen, the oxygen MFR at the secondary air-inlet (P3) is set to minimize with higher importance due to the lowest oxygen consumption which presents the operating cost. Furthermore, maximal ash temperature (P4) is set to be less than 1,300 K, the COOut (P6) is also set to minimize like the oxygen at the exit (P9). These parameters have the importance set higher. In this way we chose that the oxygen consumption is minimal with complete combustion at the exit and with lower maximal ash temperature. The parameter which is met is marked with one, two or three yellow stars and when is not achievable, the red x is written. So we can choose the final candidate manually on the basis of these three better candidates.

Table Of	denenia de ora, opuniz	au011										
•	A	В	с	D	E	F	G	н	I	J	к	L
1		P1 - InSecAirVelocity2 (m s^-1)	P2 - MSWVelocity (m s^-1)	P3 - MassInSecOxygen2	P4 - AshTempMax (K)	P5 - CH4Out	P6 - COOut	P7 - COSecIn	P8 - COSecOut	P9 - 020ut	P10 - TempOut (K)	P11 - AshTime (s)
2												
3	Objective	No Objective 🔻	No Objective 🔻	Minimize 🔻	Values <= Target 💌	No Objective 🔻	Minimize 🔻	No Objective 🔻	No Objective 🔻	Minimize 👻	No Objective 🔻	No Objective 🔻
4	Target Value				1300							
5	Importance	Default 🔻	Default 🔫	Higher 👻	Higher 🔻	Default 👻	Higher 🔻	Default 👻	Default 👻	Higher 👻	Default 👻	Default 👻
6	GDO Sample Set											
7	Candidate A	- 31,89	- 1,2264	A 0,23535	- 1341,6	- 0,0071487	★★ 0,043874	- 0,10182	- 0,061162	★ 4,3695E-09	- 803,36	*** 8,7368
8	Candidate B	- 28,65	- 1,4093	A 0,23838	- 1333,5	- 0,0072821	- 0,044692	- 0,1022	- 0,066153	🔆 4,3259E-09	- 806,21	- 8,3709
9	Candidate C	- 27,03	- 0,903	A 0,23384	× 1364,3	- 0,0070303	🔆 0,043144	- 0,10148	- 0,052481	- 4,4174E-09	- 794,81	- 10,169

Table 3. Trade-off study parameter's objective settings and results

It is can also be seen, that certain output parameters were not achieved, such as maximal ash temperature (P4) which stays higher than target value less than 1,300 K. The trade-off study process (tab. 3) can be repeated using different parameter objectives and importance, and the resultants which met the main conditions can be re-evaluated.



Figure 10. Samples chart with the best three candidates visualization



Figure 11. Response chart for maximal ash temperature *vs.* secondary air velocity and oxygen MFR in the secondary air (color image see on our web site)

enriched air is used [4, 7, 12, 16] and this phenomena is clearly seen by the temperature comparisons in this picture. On the other hand, we have to be sure that the maximum ash-temperature does not exceeded the ash melting point, and we have to avoid flying ash-deposit on heat the exchanger's walls, which can cause severe damage.

Figure 10 shows a samples chart for visualizations using the best three candidates A, B and C which are best achieved given the objectives and importance of these objectives. In this way, the precise value for each input parameter can be chosen and the calculated output parameter's valuerange can be read. The ash-residence time, for example can be predicted at between 6.5 s and 11 s or the output temperature can be between 795 K and 820 K. It can also be seen, that the maximal ash temperature cannot be less than 1,329 K, so this data should be taken into consideration.

The optimization response chart (fig. 11) which was created as a result of DOE, helps us to determinate the interaction among maximal ash-temperature vs. secondary air-velocity, and oxygen MFR in the secondary air inlet. The maximal ash-temperature from the secondary air-velocity of 27 m/s to 29 m/s increases rapidly and sets the maximum ash temperature at 1,850 K. On the other hand, there is no significant depen-dence of oxygen MFR in the region from 0.255 to 0.21. In this way we can predict and avoid the damage that can be caused by this phenomenon.

Figure 12 shows the temperature field comparison under different operating condition with different oxygen MFR (left 0.6 and right 0.232). The temperature in the secondary combustion chamber increases when oxygen-

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Figure 12. Temperature field for different oxygen MFR at secondary enriched air inlet (left – oxygen MFR 0.6 and right – MFR oxygen 0.232) (color image see on our web site)

Probabilistic sensitivities are based on a statistical correlation analysis between the individual probabilistic design variables. You can review the parameters correlation data that has been used to derive sensitivities and decide whether individual sensitivity values are significant or not. This information is collected in the correlation matrix of the random output parameters vs. the random input variables. The correlations that have been sampled between random input variables can also be reviewed. The correlations between random output parameters are important if you want to use the probabilistic results of your probabilistic analysis as input for another probabilistic analysis. When the optimization process is finished, all results can be studied and the response charts visualized.



Figure 13 shows the local parameters sensitivities among input and output parameters. It is important to know which input parameter has the influence on which output parameter and in which role (negative or positive). As can be seen, the input parameter MSWVelocity (P2) has a huge sensitivity on every output parameter and the other input parameters P1 and P3 have limited sensitivity or no sensitivity on the output parameters.

As can be seen, the CFD with additional optimization features is the most convenient tool to predict the optimal conditions which have to be achieved due to the thermal and environmental efficiency, and never to decrease the safety of the WTEP operation. With this tool we can also avoid the problems because we can predict the whole situation with appropriate inlet boundary conditions.



Figure 14. Response chart for parameter P11 – AshTime (color image see on our web site)



Figure 15. Correlation between P2 and P11

Figure 14 shows response a chart for parameter P11 - Ash Time which means the ash residence time through WTEP depends on the input of second airvelocity (P1) and MSW velocity (P2). It shows that the input second air-velocity within a range from 28 to 33 m/s, has no influence on ash-residence time. However, the ash residence time rapidly falls from 10.1 to 8.3 s when the input MSW velocity rises from 0.9 to 1.4 m/s. This finding can also be clearly seen in the correlation diagram between MSW velocity and ash residence time in fig. 15.

Response chart for maximal ash temperature (P4) is shown in fig. 16. On the one hand, the maximal ash-temperature increases rapidly from 1,300 K to 1,470 K when enriched air is used from oxygen MFR 0.25 to 0.5 at MSW velocity 1.5 m/s. At oxygen MFR 0.5 and the same MSW velocity, the temperature picked at 1,470 K then falls to 1,450 K when oxygen MFR is increased to 0.6. On the other hand, the maximal ash-temperature decreases from 1,550 to 1,450 K when the MSW velocity rises from 0.9 to 1.5 m/s. These facts should be taken into account when these input parameters change during operating WTEP, due to the ash-melting point and oxygen consumption and operating costs, respectively.

Figure 17 shows 3-D ashtemperature particle tracking through the WTEP. The ashtemperature changes through the WTEP and was picked in the secondary combustion chamber where the oxygen-enhanced combustion is used. In addition, the ash temperature has fallen due to the wall cooling. It was discovered when the flaying ash crashed into the walls and the probability of ash-deposit at these sections is high.

Streamlines with velocity review is shown in fig. 18. It can be seen, that the majority of the streamlines take the short way through the WTEP and the



Figure 16. Response chart for parameter P4 – AshTempMax (color image see on our web site)

velocity becomes higher at the exit of the secondary chamber. It must be taken into consideration when the residence time is predicted.



Figure 17. Ash temperature particle tracking (color image see on our web site)

Figure 18. Streamlines with velocity review (color image see on our web site)

Spider charts (figs. 19 and 20) allows you to visualize the impact that changing input parameters has on all of the output parameters, simultaneously. Figure 19 shows the impact at input parameters P1 = 30 m/s, P2 = 1.2 m/s, and P3 = 0.232 on the output parameters and fig. 20 shows the impact at input parameters' maximal ash temperature by P1 = 30 m/s, P2 = 1.2 m/s, and $P3 = 0.6 \text{ which means that the oxygen enhanced combustion (OEC) is applied. The maximal ash temperature (P4) rises from 1,345 K to 1,465 K when the OEC is performed. The oxygen mass fraction at output (P9) is tripled and, on the other hand, the rest of the output parameters and output parameters becomes easily scanned.$

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Figure 19. Spider chart of maximal ash-temperature for P1 = 30 m/s, P2 = 1.2 m/s and P3 = 0.232

Figure 20. Spider chart of maximal ash-temperature for P1 = 30 m/s, P2 = 1.2 m/s and P3 = 0.6



Figure 21. Linear correlation matrix (color image see on our web site)

Figure 21 shows the linear correlation matrix among input and output parameters. Correlation matrix allows you to visualize how closely the various input and output parameters are coupled. the strength of correlation is indicated by different colours in the matrix, which can be read in the matrix legend. Each parameters are indicated twice on the main row and on the main column. Placing your cursor over a particular square will show you the correlation value for the two parameters associated with that square. In the diagonal direction, the same parameter is crossed and marked with red color, which means that the strength is 1. On the other hand, the correlation strength between P9 and P5 or P9 and P6 is -1. The correlation strength between two parameters can be between +1 and -1, which can also be seen in the matrix legend. In this way, the correlation matrix has a huge value due to the

correlation among the whole input and output parameters being easily seen in the one correlation matrix.

Conclusions

The applicabilities of various combustion operating conditions was examined and analyzed, based on the real operating conditions. The CFD approach and the numerical optimization is used to identify, the appropriate conditions to achieve complete combustion conditions, minimize the pollutants emission, operating troubleshooting and keeping operational costs at a reasonable level. The input and output parameters were also studied and visualized in the response and spider charts. The local sensitivities among different parameters were presented graphically. Furthermore, some input and output parameters correlation was discovered and presented with charts, and also through the easily scanned linear correlation matrix.

This paper has shown huge benefits with the CFD approach, and specially the numerical optimization of the operating condition. These conditions which are presented as the input parameters varied between reasonable operating conditions and output parameters, which were previously defined, were predicted. In this way, certain important values for each output parameters without expensive and long-duration measurements and different operating conditions having been established. On the other hand, the goal-driven optimization has shown which candidates successfully met all our input requirements based on the objectives and importance which were defined previously.

Practically, by using numerical optimization the damage can be avoided, which can be caused by overheating or exceeding the ash melting point temperature. In addition, the needed residence time which is legally-regulated can be predicted under different operating conditions, and never the last to find out the input and output parameter interactions or correlations.

Finally, further simulations have to be done to include the geometrical dimensions as input parameters and find out the correlation on output parameters. The geometrical dimensions should also be included in the response charts, parameter's sensitivities, and in the linear correlation matrix. In this way, this optimization can be used, not only for operating parameter's prediction of real WTEP but also during the project phase which would reduce the research and development costs.

Nomenclature

cp	- specific heat capacity at constant
	pressure, [m s K]
D_k	 molecular diffusion coefficient of
	component k, [kgm ⁻¹ s ⁻¹]
$\overline{f_{\rm vi}}$	- sum of all volume forces, [kgm ⁻² s ⁻²]
\overline{h}	- enthalpy, $[m^2 s^{-2}]$
$\overline{I_{\rm R}}$	 radiation source/sink terms, [kgm⁻¹s⁻³]
$I_{\rm T}$	 – energy source/sink terms, [kgm⁻¹s⁻³]
M_k	- molecular mass of the component k ,
	[kgkmol ⁻¹]
р	- pressure, [kgm ⁻¹ s ⁻²]
Prt	- turbulent Prandtl number, (= $c_p \mu_t / \lambda_t$),[-]
7	1

- heat flux, $[kgm^{-1}s^{-3}]$

- turbulent Schmidt number, $(= \check{z}_t / \check{z}_t), [-]$ Sc.

Т - absolute temperature, [K]

Greek letters

- turbulent diffusivity, $[kgm^{-1}s^{-1}]$ Ž₊
- Kronecker delta function, [-]
 turbulent viscosity, [kgm⁻¹s⁻¹] Ž_{ii}
- Žt
- $\frac{\overline{\rho}}{\overline{\tau}_{ij}}$ – density, [kgm⁻³]
 - viscous stress tensor, $[kgm^{-1}s^{-2}]$
- fluid velocity, [ms⁻¹] Ži

Acronyms

CFD - computational fluid dynamics

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GDO	– go	bal driven optimisation	MSW	_	municipal solid waste
MFR	– m	ass fraction of component,	NLPQL		non-linear programming by the quadratic
MOGA	(<i>n</i> – m	u_i/m_{tot}), [–] ulti-objective generic algorithm	WTEP	_	Lagrangian waste-to-energy plant

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