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Numerical Analysis of Aluminium Extraction from Packaging Waste Utilizing Arc Plasma†

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This study is a preliminary study for the pre-design of thermal recycle gasification melting furnace. This study is aimed to reduce the impediments during actual operation, derive the basic design factors for economic design through numerical analysis and to obtain data to establish operating variables. This study conducted a numerical analysis under different plasma torch temperature conditions such as 2600, 2800, 3000 and 3200 K. The result showed that when the temperature conditions are 2,600 and 2,800 K, the high temperature formed in A area near the plasma torch are not delivered to the entire furnace or evenly distributed and a local low temperature zone is formed around C zone since complete mixture with the internal fluid did not occur due to the inducement of the oxygen at room temperature. This occurred in both conditions because the temperature required for firing reaction did not reach 1620 K, which is expected to disturb the smooth processing in aluminum extraction and reducing the time required to form the ambient temperature in the furnace. On the contrary, when the plasma torch temperatures are 3000 and 3200 K, the temperature inside the furnace is evenly distributed at 1700 K or above. It is considered that there is no solidification problem in aluminum melting and firing reaction in both condition.

Keywords: Thermal recycle, Gasification melting furnace, Numerical analysis, Aluminum extraction, Plasma torch temperature.

INTRODUCTION

Recently, waste increases and diversifies as various manufactured products increase due to urban concentration of population and industrial development, disposable products increase from the pursuit of convenience, increase of instant food and increased needs from the improved standard of living. Environmental pollution and waste treatment became the various source of pollution of water quality, air and soil home and abroad, so interests are growing about the safe treatment of the wastes[1,2]. Accordingly, waste management policies are being established to minimize waste to conserve nature and maintain human health by minimizing the waste that returns to nature, minimizing resources exploitation and using resources effectively[3,4].

Among the wastes, aluminium is a metal substance with excellent mechanical properties including light weight, good workability and corrosion resistance; is in the spotlight as a key engineering material that increases the mechanical properties[5] by alloying with other elements like copper, magnesium, silicon, zinc, nickel, manganese or silver.

Aluminium is widely used in chassis, automobiles and packaging material, *etc*.: aluminium used for chassis, automobiles is recycled, but aluminium-included packaging material, or multiple film waste is not recyclable in Korea but is treated by incineration or landfill. To resolve this problem, plasma pyrolysis gasification melting furnace may be designed to extract aluminium, resolving the lack of mineral resources and producing the Syngas which may be used as the energy source contributing to the development of alternative energy[6-8].

The object of this basic research is the preliminary design of pyrolysis gasification melting furnace to extract aluminium from the multiple film waste using plasma pyrolysis gasification technology and data acquisition to establish operating parameters, deriving basic design factors through computer analysis for economical design and reducing obstacles that may occur in the actual operation[9,10].

EXPERIMENTAL

Theoretical approach method: Numerical analysis should be performed considering interaction of the arc and

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gas generated in the plasma, mixing effect of surrounding gases and momentum and energy of each plasma. However, the analysis would be very complicated with all these factors considered. Therefore, under the assumption arc was discharged and is high temperature fluid, numerical analysis was performed using commercial code, FLUENT12 focused on the degree of mixing of raw gases and the quantity of state of the flow field[11]. Standard $\kappa-\varepsilon$ model was used for the analysis of the turbulence flow field consisting two different states of physical properties like density and temperature. The turbulence intensity is defined as the following.

$$I=\frac{\sqrt{(u')^2}}{u_{\alpha vg}}$$

where, turbulence intensity is defined as the ratio of root mean square of the mean velocity ($u_{\alpha vg}$) and the velocity fluctuation (u'). SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used to compute the pressure under the assumption of the steady state steady flow (SSSF). Unsteady state was also assumed to find the physical change during the process to reach the Al melting point in the furnace[12].

Governing equations: To have a understanding of the characteristic analysis and mixing process of the plasma-formed flow field, the following equations were used including equation of continuity, momentum equation, energy equation and turbulence transport equation.

Equation of continuity: The equation of continuity is as follows.

$$\frac{\partial\rho}{\partial t}+\nabla(\rho\vec{v})=0$$

where, $\vec{v}$ is the mean velocity and ρ is the density.

Momentum equation: The momentum of the entire gases can be expresses as the sum of the momentum of each gas.

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla(\rho\vec{v}\vec{v})=\nabla P+\nabla(\Gamma)+\rho\vec{g}+\vec{F}$$

where, $\vec{F}$ is the mass force and represents the stress tensor.

$$\Gamma=\mu[(\nabla\vec{v}+\nabla\vec{v}^T)-\frac{2}{3}\nabla\vec{v}I]$$

where, μ is the molecular viscosity, I is the unit tensor.

Energy equation:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}\alpha_k\rho_k E_k+\nabla\sum_{k=1}^{n}(\alpha_k\vec{v}(\rho_k E_k+p))=\nabla(k_{eff}\nabla T)+S_E$$

where, κ_{eff} means the effective thermal conductivity ($\Sigma a_k(k_k+k_t)$), k_t means the turbulence thermal conductivity and S_E means the heat source term. For compressible gases:

$$E_k=h_k-\frac{P}{\rho_k}+\frac{v_k^2}{2}$$

For non-compressible gases: $E_k = h_k$

where, h_k is the enthalpy of gas k.

Energy equation turbulence transport equation (standard k – ε model): Turbulence motion energy κ and its dissipation rate ε are found by the following transport equation.

$$\frac{\partial}{\partial t}(\rho\kappa)+\frac{\partial}{\partial\chi_i}(\rho\kappa u_i)=\frac{\partial}{\partial\chi_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial\kappa}{\partial\chi_j}\right]+G_k+_b-\rho\varepsilon$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial\chi_i}(\rho\kappa u_i)=\frac{\partial}{\partial\chi_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial\chi_j}\right]$$

$$+C_{1\varepsilon}\frac{\varepsilon}{\kappa}(G_k+C_{2\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa}$$

In these equations, G_κ represents the turbulence kinetic energy generation from the mean velocity gradient. G_b refers to the turbulence energy generation by buoyancy, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are constants and σ_κ and σ_ε are turbulence Prandtl numbers for κ and ε.

The turbulence viscosity coefficient μ_t is computed from the combination of κ and ε as the following.

$$\mu_t=\rho C_u\frac{\kappa^2}{\varepsilon}$$

Numerical analysis conditions

Boundary conditions: Ambient temperature should be made to enable the melting of the aluminium thin film waste during the operation of the furnace. The temperature is measured by the flame temperature of the arc plasma. The flame temperature is determined by the electric power, but it is limited to express all the physical phenomena in the numerical analysis, so arc flame was assumed as a fluid and the furnace ambient temperature was observed depending on the arc flame temperature. In addition, the temperature distribution in the furnace was analyzed at sections A, B, C equally spaced throughout the furnace and the effect to the temperature caused by the injection of oxygen. Optimal temperature condition was found to compute the time taken from that temperature to aluminium melting using 2D lattice. Time was measured for the entire aluminium thin film waste to reach to melting point for the analysis at sections D, E, F considering the heat of 10.711 kJ mol^{-1} which corresponds to the latent heat of fusion necessary for the state change of aluminium thin film waste from solid to liquid. Calculation grids are shaped as non-structured three-dimensional triangles with the number of 2.5 million.

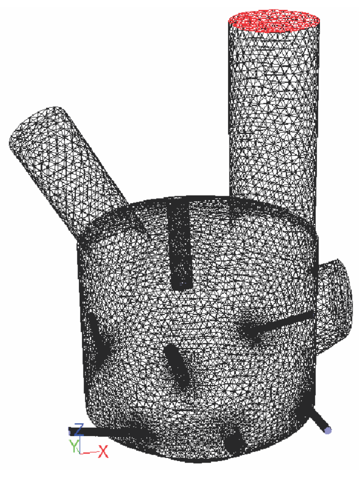


Fig. 1. Schematic diagram of mesh

TABLE-1
SIMULATION CONDITION OF CFD ANALYSIS

Grid number	3D: About 2,500,000, 2D: About 19,000
Inlet_plasma	Temperature: 2600, 2800, 3000 and 3200 K, Velocity: 30 m/s
Inlet_O2	Temperature: 293 K, velocity: 5 m/s
Outlet	Pressure: 1 atm
Applied model	Standard κ – ε model, Steady state

TABLE-2
PROPERTIES OF INORGANIC ELEMENTS

Element	Al	Cu	Fe
Mass (g)	26.98	63.55	55.85
Density (kg/m^3)	2719	8978	8030
Cp (Specific heat) (J/kg-K)	871	381	502.48
Thermal conductivity (w/m-K)	202.4	387.6	16.27
Melting point (K)	933	1358	1809
Boiling point (K)	2790	2843	3133
Latent heat of fusion (kJ mol^{-1})	10.711	13.138	13.807

RESULTS AND DISCUSSION

Flow characteristics by plasma torch temperature

When torch temperature is 2600 K or 2800 K: It is considered that aluminium melting occurs locally near the plasma torch because the temperature distribution will not be uniform throughout the entire range since the high temperature formed at A region near plasma torch when the plasma torch temperature is 2600 K or 2800 K. In addition, C region formed by incomplete mix with interior fluids of injected oxygen of room temperature is local low temperature region. This region, 9 % of the total volume, does not affect very much to the melting reaction of aluminium, but is supposed to interfere with the vitrification due to the lower temperature than 1620 K which is necessary to waste vitrification. Under these two conditions, the coagulation of the locally vitrified waste hinders smooth extraction process of aluminium; and cannot reduce the time taken to reach the ambient temperature of the furnace (Figs. 2 and 3).

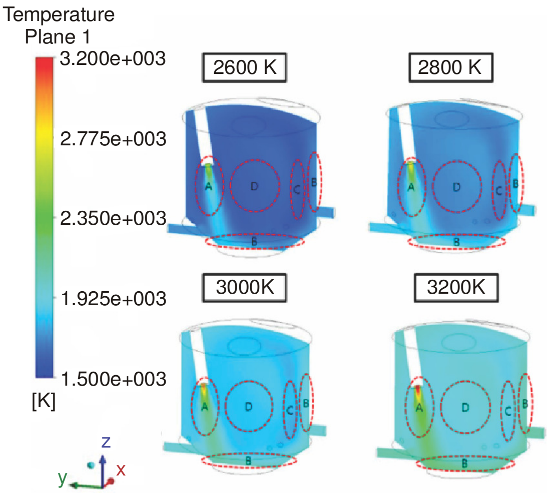
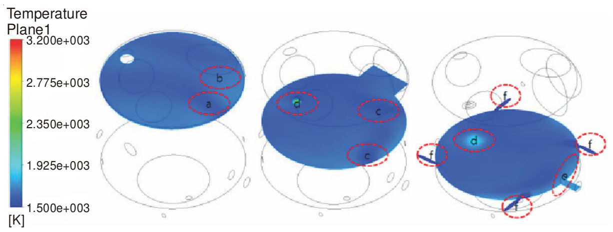
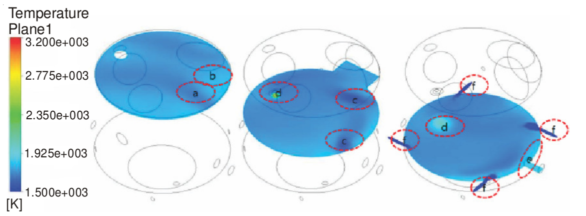


Fig. 2. Furnace temperature distribution as a variation of temperature

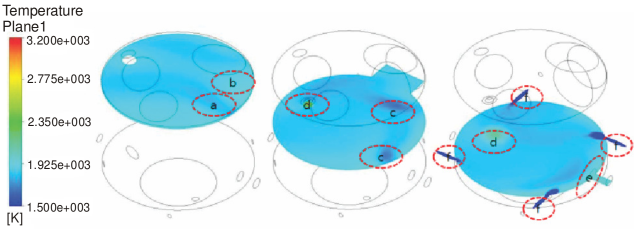
When torch temperature is 3000 K or 3200 K: When plasma torch temperature is either 3000 K or 3200 K, the temperature distribution was uniform above 1700 K in the furnace, so it is supposed that there is not coagulation in aluminium melting and waste vitrification. However, it is not considered to be an effective operation to maintain the plasma torch temperature higher increasing energy consumption, for the temperature already got to stable region over 3000 K. It is advised to maintain 3000 K normally and to raise the temperature above 3000 K when the treatment throughput increases sometimes (Figs. 2 and 3).



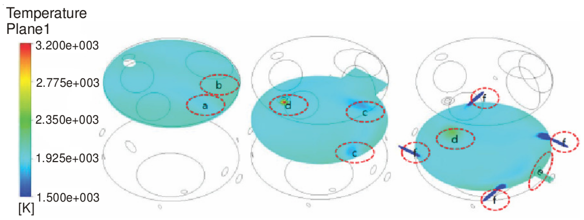
(a) Plasma torch at 2600 K



(b) Plasma torch at 2800 K



(c) Plasma torch at 3000 K



(d) Plasma torch at 3200 K

Fig. 3. Horizontal temperature distribution in plasma torch (a, b, c, d)

Conclusion

This study is a basic research for the preliminary design of the pyrolysis gasification melting furnace; the goal is to reduce obstacles occurring during actual operation, to derive basic design parameters through computer analysis and to acquire data to establish operating parameters. Numerical analysis was performed with the plasma torch temperature of 2600, 2800, 3000 and 3200 conditions: 2600 K or 2800 K conditions are thought to cause local melting of aluminium near the plasma torch due to the uneven temperature distribution in the interior of the furnace and to harm waste vitrification due to the local formation of low temperature range in C region from the incomplete mixing of injected oxygen and the internal gases. These phenomena occurs in both cases due to the lower temperature than 1620 K which is necessary for the waste vitrification, harming satisfactory waste vitrification and time reduction taken to form ambient temperature of the furnace. Meanwhile, ambient temperature of 3000 K or 3200 K showed uniform temperature distribution above 1700 K, excluding the potential coagulation during aluminium melting and waste vitrification. It is not recommended still to maintain the plasma torch temperature unnecessarily higher than 3000 K which is the stable temperature already reached. It will not be an effective operation and energy wasting. It will be effective to maintain the temperature at 3000 K normally and to utilize higher temperature range that 3000 K sometimes when the treatment demand is high.

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