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Estimation of Electrical Power and Radio Frequency of an Induction Heater for Corium Melting Using a Cold Crucible

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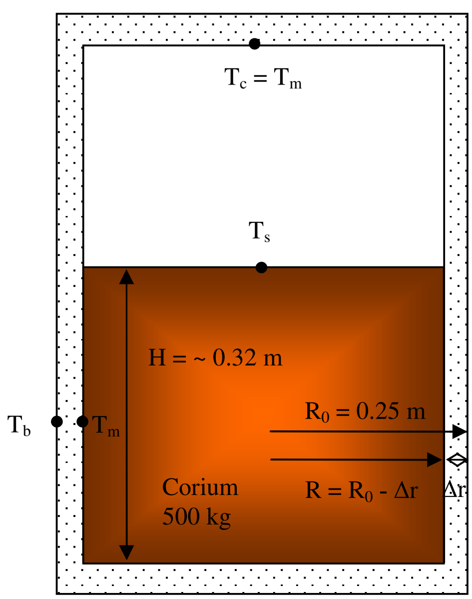
1. Introduction

The melting of corium is needed for the evaluation of the APR+ core catcher concept for the core debris coolability during a hypothetical severe accident in a nuclear reactor. KAERI has decided to apply an induction heating method using a cold crucible for the purpose. A simple estimation is introduced here to determine the electrical power input and radio frequency of the induction heater.

2. Design of an Induction Heater

The corium (the mixture of UO_2 and ZrO_2) mass to be melted in the crucible was chosen to be 500 kg. A cold crucible method is determined to be used for its advantage in costs. This method is applied by flowing water into the copper tubes forming the crucible wall. This flowing water allows a thin sintered layer of corium in the vicinity of the inside wall of the crucible to serve as a self-crucible. Fig. 1 shows the schematic diagram of the corium melt in the cold crucible.



T_m = Melting temperature of corium
T_b = Bulk temperature of water
D = 0.5 m, H = 0.32 m, M = 500 kg

Fig. 1. Schematic diagram of the corium melt in the cold crucible

The inner diameter of the cold crucible was decided to be 0.5 m (R_0). The thickness of the sintered layer is denoted to be Δr.

The induction power input (q_{in}) into the cold crucible should be larger than the sum of the heat loss (q_{loss}) and the power for superheat $q_{superheat}$). Heat loss resulted from the upward radiation and the conduction through the side wall (q_{side}) and bottom (q_{down}).

First, the upward radiation heat loss (q_{rad}) is denoted to be as follows. From Eq. (1), q_{rad} is estimated to be 132 kW.

$$q_{rad} = \sigma\varepsilon\,(T_s^4 - T_c^4)\,A_{up} \quad (1)$$

where,

$\sigma = 5.67*10^{-8}$ J/m^2·K^4·s, ε= 0.79,
$A_{up} = \pi R^2 \approx \pi R_0^2 = 0.0625\pi$,
$T_c = T_m$ ~ 2850 K, T_s = 3000 K

In order to estimate the power for superheat ($q_{superheat}$) and the conduction heat loss (q_{cond}), a steady state conduction heat transfer is assumed in the corium region. This assumption will not mislead the heat loss so much since the conduction heat loss is a small fraction as to be seen later.

The temperature profile in the corium melt calculated from conduction and the average temperature of the melt are presented in Eqs. (2) and (3).

$$T_1(r) = -\frac{q'''}{4k_f}(r^2 - R^2) + T_m \quad (2)$$

$$\overline{T_1} = T_m + q'''_{superheat}\left(\frac{R^2}{8k_f}\right) = T_m + \frac{q_{superheat}}{8\pi H k_f} \quad (3)$$

where, k_f (corium conductivity) = 2.88 W/K·m

It means that the average temperature ($\overline{T_1}$) increases with an increase in melt radius (R) and a decrease in melt height (H). From Eq. (3), the input power of only 5 kW is needed to achieve a superheat of 200 K.

In order to estimate the conduction heat loss through the side wall, the conduction equation in the sintered layer (porous media) is solved to be Eq. (4) as follows.

$$T_2(r) = C_1 \ln r + C_2 \quad (4)$$

where, $C_1 = \dfrac{(T_b - T_m)}{\ln\left(\dfrac{R + \Delta r}{R}\right)}$

From the boundary condition of the same heat flux on the boundary between the melt and the sintered layer, following equations are obtained.

$$-k_f \frac{dT_1}{dr}\bigg|_R = -k_p \frac{dT_2}{dr}\bigg|_R$$

$$\frac{q'''R}{2} = \frac{(T_m - T_b)}{\ln(\frac{R+\Delta r}{R})}\frac{k_p}{R} \qquad (5)$$

$$\frac{R+\Delta r}{R} = \exp[\frac{2k_p}{q'''R^2}(T_m - T_b)]$$

$$= \exp[\frac{2\pi H k_p}{q_{side}}(T_m - T_b)] = \exp(\frac{502}{q_{side}})$$

$$\Delta r = R_0\{1 - \exp(-\frac{502}{q_{side}})\} \qquad (6)$$

where, k_p (conductivity of the sintered layer) ~ 0.098 W/K·m, T_m = 2850 K, T_b = 300 K, $q_{side} = q_{in} - (q_{superheat} + q_{rad} + q_{down})$

The conductivity of the sintered layer (k_p) is calculated from the following concept [1] using physical properties of k_f ~ 2.88 W/K·m and k_{air} ~ 0.05 W/K·m, with an assumption of 0.5 in porosity.

$1/k_p = f_f/k_f + f_{air}/k_{air} = 0.5/2.88 + 0.5/0.05 = 10.17$

The conduction heat loss through the side wall according to the thickness of the sintered layer is estimated and presented in Table I.

Table I: Conduction heat loss through the side wall

q_{side} (kW)	10	20	40	50
Δr (mm)	10.2	6.2	4.1	2.5

Then, the conduction heat loss through the bottom is estimated to be ~ 40 % from the comparison of the heat transfer area between the sidewall ($A_{side} = 2\pi RH$) and bottom ($A_{down} = \pi R^2$).

Total heat loss by conduction is estimated to be 56 kW when the sintered layer is 4.1 mm in thickness.

Therefore, the order of the magnitude in heat loss is that by radiation, conduction and superheat for the corium melt at a steady state. The total heat loss by radiation, conduction and superheat is calculated to be about 200 kW.

Considering the efficiency of the induction heating (50 ~ 60 %), about 400 kW of the electrical power input needs to be supplied for the melting of 500 kg of corium.

Meanwhile, the radio frequency of the induction heater is to be determined, since it is deeply related to penetration depth of the material to be melted. The penetration depth is recommended to be 10 % of the crucible diameter. The crucible diameter is 0.5 m, so the penetration depth of 5 cm is recommended. The penetration depth depends on electrical resistivity of the melt and radio frequency, as presented in Fig. 2 [2]. Since the electrical resistivity of corium at the melting point (~ 2850 K) is 4×10^{-3} Ω·cm and penetration depth is 5 cm, the radio frequency is determined to be about 10 kHz. Considering that the electrical resistivity of the solid corium preheated by an initiator (oxidation of Zr metal) is higher (~ 0.025 Ω·cm at 2000 K), the radio frequency of the induction heater is recommended to be 10 ~ 50 kHz.

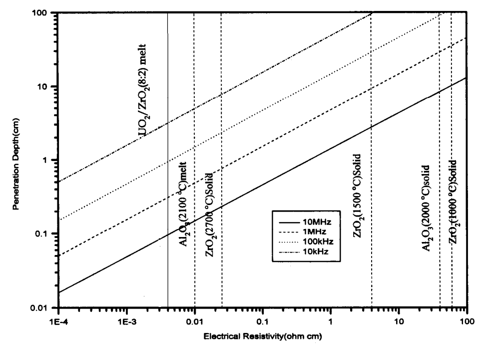


Fig. 2. Dependence of penetration depth on electrical resistivity and radio frequency

3. Conclusions

The electrical power and radio frequency of an induction heater for corium melting using a cold crucible are estimated with a relatively simple method. About 400 kW of electrical power and 10 ~ 50 kHz of radio frequency are needed for the melting of 500 kg of corium. This method can be easily applied to the design of an induction heater using a cold crucible.

REFERENCES

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