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Temperature Distribution in Floor Constructions under Thermal Units

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ABSTRACT

A computational algorithm for determining of temperature distribution at multilayer floor constructions bearing cooking convection ovens is developed. It was applied for estimation of the temperatures in the floor layers under an oven at different configurations and materials. Guidelines for the implementations of the bearing construction are discussed on the base of the thermal analysis.

Keywords: heat transfer, convection ovens, thermal insulation, temperature distribution, floor constructions.

INTRODUCTION

Although the concrete is a non-combustible material, the reinforced concrete structures continuously exposed to high temperatures have some problems with durability, reliability and mechanical performance [1]. Therefore, the possible thermal loads have to be taken into account at the design stage to avoid the decreasing of the quality of the materials.

It is especially important to predict these processes for floor constructions bearing ovens and furnaces, which are loaded both thermally and mechanically. The investigations show that the tensile and the compressive strengths of the concrete are decreased at temperature rise from 20 to 800°C. The rate of the decreasing is slower until 300°C and higher after this temperature. Therefore, a refractory concrete is recommended for the floor slabs at expected temperatures over 100°C.

Detailed three-dimensional temperature fields in the constructions can be obtained via numerical solution of the energy equation by finite elements or finite differences method. These approaches give results that are more accurate however require specialized software and hardware [2].

The aim of the present investigation is to propose and test a simple and easy for use numerical procedure allowing the determination of the temperature distribution in multilayer floor construction, bearing high temperature convection ovens for cooking.

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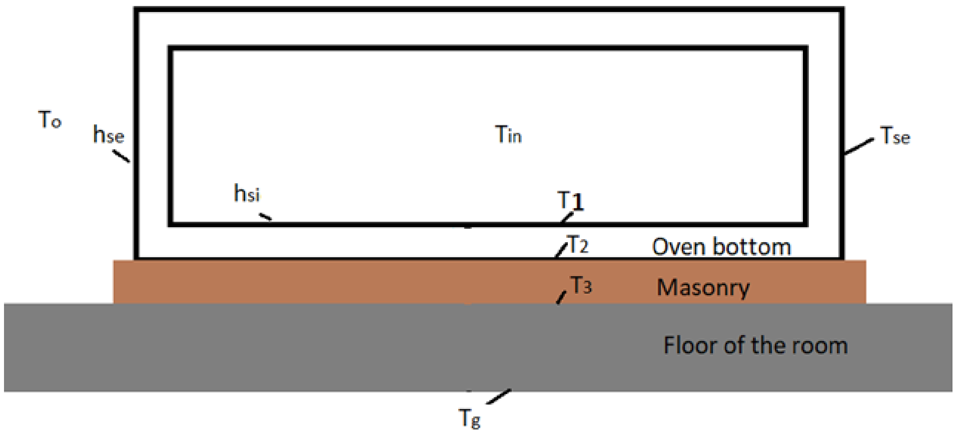

Fig. 1. A floor construction under an oven.

Heat transfer in floor structures bearing convective ovens

Various standard phrases are used to classified the ovens in the cooking according to the temperature ranges they are used (Table 1). The heat transfer in them can be a combination between radiation and convection, depending on the energy supply and the construction.

Usually the convection ovens are mounted at a distance from the floor via legs or other similar constructions. The thermal losses through the oven envelopes are relatively small at the low temperature units. They can be computed at known (measured) temperatures T_{se}, (K) of the external surfaces. The heat flux $\dot{q}$ (Wm^{-2}) through the oven envelopes is:

$$\dot{q} = h_{se}(T_{se} - T_o) \quad (1)$$

The coefficient of heat transfer h_{se} from the external surfaces of the oven to the environment is consisted of two parts, reflecting the heat exchange by convection and radiation [5]:

$$h_{se} = A\sqrt[4]{T_{se} - T_o} + \varepsilon C_s \frac{\left[\left(\frac{T_{se}}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4\right]}{T_{se} - T_o} \quad (2)$$

where T_o - ambient temperature, K; ε - emissivity of the external surface; C_s - 5.67 W m^{-2} K^{-4} – Stefan-Boltzmann coefficient for absolutely black body; A - 2.6 for vertical hot surfaces; A - 3.3 for top hot surfaces and A - 1.6 for bottom hot surfaces.

At the cases of units, supported by legs, the hot external surfaces of the bottom exchange heat by convection with the air space and by radiation with the floor under the oven (surface to surface radiation). The temperature T_o in eqs. (1) and (2) depends on the distance between the bottom of the oven and the floor, and can be determined iteratively.

The high temperature ovens can be placed on solid bearing layers (base) on the floor in other to reduce the thermal losses (Fig. 1). These layers have to be with enough mechanical strength and

Table 1. Temperature ranges of cooking ovens [4].

Description	Temperature range, °C
Cool oven	90°C
Very slow oven	120°C
Slow oven	150 - 160°C
Moderately slow	160 - 180°C
Moderate oven	180 - 190°C
Moderately hot	190 - 200°C
Hot oven	200 - 230°C
Very hot oven	230 - 260°C
Fast oven	230 - 300°C
Neapolitan pizza	485°C

relatively low thermal conductivity. That activity will reduce the heat transfer through the bottom of the oven but also will load thermally the main floor slabs. The temperature distribution in such constructions can be obtained via the above approach.

As stationary processes if the thermal bridges in the oven corners can be neglected, the temperatures field in the floor construction on Fig. 1 can be considered as one-dimensional and the heat flux is:

$$\dot{q} = \frac{T_{in} - T_g}{R_{si} + R_o + R_m + R_f} = \frac{T_{in} - T_2}{R_{si} + R_o} = \frac{T_{in} - T_3}{R_{si} + R_o + R_m} =$$

$$= \frac{T_2 - T_3}{R_m} = \frac{T_3 - T_g}{R_f} \quad (3)$$

where T_{in} - internal temperature of the oven, K; T_g - ground temperature, K; T_2 - temperature of the boundary between the oven bottom and the masonry, K; T_3 - temperature of the boundary between the masonry and the floor surface, K. R_{si} is the resistance of the inner thermal boundary layer, $m^2 KW^{-1}$:

$$R_{si} = \frac{1}{h_{si}} \quad (4)$$

where h_{si} - coefficient of heat transfer from the oven space to the bottom of the oven, $Wm^{-2} K^{-1}$.

R_o, R_m and R_f are the thermal resistances of the oven bottom, masonry and floor layers, respectively, $m^2 KW^{-1}$. They are computed as for multilayer constructions in the common case:

$$R = \sum_{i=1}^{n} \frac{\delta_i}{K_i} \quad (5)$$

where δ_i = i-th layer thickness, m; K_i = thermal conductivity of the i-th layer, $Wm^{-1}K^{-1}$.

The summary thermal resistance R_b of the oven bottom:

$$R_b = R_{si} + R_o \quad (6)$$

can be obtained by the heat flux equation knowing the external temperature in the case the oven is supported by legs:

$$\dot{q} = \frac{T_{in} - T_o}{R_b + R_{se}} = \frac{T_{se} - T_o}{R_{se}} = h_{se}(T_{se} - T_o) \quad (7)$$

This is correct as the thermal field in the oven space is maintained automatically and do not depend on the floor construction, or:

$$R_b = \frac{T_{in} - T_{se}}{h_{se}(T_{se} - T_o)} \quad (8)$$

The ground temperature is usually known [6]. Therefore, the temperatures T_2 and T_3 can be calculated using different variants of eq. (3):

$$T_2 = T_{in} - \frac{R_b(T_{in} - T_g)}{R_b + R_m + R_f} \quad (9)$$

$$T_3 = T_{in} - \frac{(R_b + R_m)(T_{in} - T_g)}{R_b + R_m + R_f} \quad (10)$$

The temperatures at the boundaries at the sublayers of the masonry and the floor construction can be determined using the same approach, if it is necessary.

Temperature distribution in floor construction supporting a high temperature oven

The suggested approach is used for computing the temperature distribution at four variants of floor constructions, bearing a continuous working electrical convection oven. The oven construction is covered with a steel casing with emissivity ε - 0.8. The sizes of the bottom (1.7 m x 1.7 m) are approximatively six time higher than the thickness of the solid base, so the temperature field can be assumed as one-dimensional with a sufficient accuracy. The calculations are implemented at the maximal internal temperature of the oven t_{in} - 450°C (T_{in} - 723 K).

The first variant is a supporting construction with legs at a relatively high distance between the oven and the floor. According to industrial experiments the temperatures of all external surfaces at this variant are t_{se} = 120°C (T_{se} - 93 K).

A refractory masonry (mullite) is used as a

Table 2. Floor constructions.

Layer	Material	Thickness δ, m	Thermal conductivity $Wm^{-1}K^{-1}$	Thermal resistance R, m^2KW^{-1}
Variant 2				
1	Oven bottom	Not required for analysis		See Table 3
2	Fireclay masonry mullite JM 30 [7]	0.250	0.43	0.581
3	Reinforced concrete [6]	0.200	1.63	0.123
4	Concrete with crushed waste bricks [6]	1.000	1.02	0.980
Variant 3				
1	Oven bottom	Not required for analysis		See Table 3
2	Ceramic fiber blanket [8]	0.020	0.09	0.222
3	Fireclay masonry mullite JM 30 [7]	0.250	0.43	0.581
4	Reinforced concrete [6]	0.200	1.63	0.123
5	Concrete with crushed waste bricks [6]	1.000	1.02	0.980
Variant 4				
1	Oven bottom	Not required for analysis		See Table 3
2	Ceramic fiber blanket [8]	0.250	0.09	2.778
3	Reinforced concrete [6]	0.200	1.63	0.123
4	Concrete with crushed waste bricks [6]	1.000	1.02	0.980

base of the oven at Variants 2 and 3 according to Fig. 1. The mullite has enough mechanical strength and relatively low thermal conductivity. Additional layer of ceramic fiber blanket is placed between the oven and the mullite at Variant 3.

Variant 4 is also supporting construction with legs, however the space between the oven and the floor is filled with ceramic fiber blanket.

The floor of the room is two-layer. The ground temperature is accepted according to [6] t_g - 10°C (T_g - 283 K). The parameters of Variants 2, 3 and 4 are summarized in Table 2. The results about the temperatures and thermal loses are presented in Table 3. The refractory and blanket layers insulate the bottom of the oven and reduce significantly the thermal loses through it. However, the temperature of the concrete surface of the floor is higher than 100°C for Variants 2, 3 and 4 and can cause a decreasing of its quality. The adding of a ceramic fiber blanked increase the thermal resistance of the construction at Variant 3, but its mechanical stability is reducing due to the lower density of the material (about 130 kg m^{-3}). Actually the ceramic fiber layer will be pressed and crushed by the oven, that will not destroy it and will not make worse its functionality, but will increase its thermal conductivity. These negative effects are avoided at Variant 4, but the height of the ceramic fiber blanket is not enough to reduce the temperature on the concrete layer of the floor.

Table 3. Results.

Parameter	Dimension	Value
Variant 1		
Heat transfer coefficient at the external surface of the oven bottom at a high distance from the floor h_{se}	$Wm^{-2}K^{-1}$	12.547
Thermal resistance of the oven bottom R_b	m^2KW^{-1}	0.263
Heat flux according to eq. (1) at ambient temperature 20 °C (T_o=293 K)	Wm^{-2}	1255
Variant 2		
Temperature between the bottom of the oven and the mullite T_2 / t_2	K / °C	664 / 391
Temperature between the mullite and the concrete slab of the floor T_3 / t_3	K / °C	532 / 259
Heat flux through the construction	Wm^{-2}	226
Variant 3		
Temperature between the bottom of the oven and the ceramic blanket T_2 / t_2	K / °C	670 / 397
Temperature between the mullite and the concrete slab of the floor T_3 / t_3	K / °C	507 / 234
Heat flux through the construction	Wm^{-2}	203
Variant 4		
Temperature between the bottom of the oven and the ceramic blanket T_2 /t_2	K / °C	695 / 422
Temperature between the ceramic blanket and the concrete slab of the floor T_3 /t_3	K / °C	400 / 127
Heat flux through the construction	Wm^{-2}	106

CONCLUSIONS

The use of refractory and insulating solid layers in the bearing construction reduce the thermal loses through the bottom of the high temperature ovens for cooking but increases the temperatures of the floor layers under the unit. Therefore, such constructive solutions have to be analyzed thermally and précised on design stage if the floor slab is not made of refractory concrete.

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