

Non isothermal drying process optimisation - Drying of clay tiles

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Abstract. In our previous studies we have developed a model for determination of the variable effective diffusivity and identification of the exact transition points between possible drying mechanisms. The next goal was to develop a drying regime which could in advance characterize the real non isothermal process of drying clay tiles. In order to do this four isothermal experiments were recorded. Temperature and humidity were maintained at 350C / 75%; 450C / 70%; 450C / 60% and 500C / 60%; respectively in each experiment. All experimentally collected data were analyzed and the exact transition points between possible drying mechanisms were detected. Characteristic drying period (time) for each isothermal drying mechanism was also detected. The real, non-isothermal drying process was approximated by 5 segments. In each of these segments approximately isothermal drying condition were maintained. Temperature and humidity of the drying air, in the first four segments, was maintained on the same level as in recorded isothermal experiments while in the fifth segment, it were maintained at 700C / 40%. The duration of the first four segments were calculated from the diagrams $Deff - t$ respectively for each experiment. The clay tile in experiment five was dried without cracking using the proposed non isothermal drying regime.

1. Introduction

Drying is very important process in the production of clay tiles. In our previous articles [1-4] calculation methods and computer programs designed for determination of the effective diffusion coefficient were presented. All reported models were created for isothermal conditions. Using those programs and calculation methods we were also able to calculate the variable effective diffusivity, to divide drying curve in segments and to identify the exact transition points between possible drying mechanisms.

Typical curves which represents the dependence of the effective moisture diffusivity as a function of the moisture content or drying time obtained using our calculation method [3] are presented at figure 1. All possible mechanisms of moisture transport and their transition from one to another during the constant and the falling drying period are well identified and are shown at figure 1. Drying segments along with mechanisms that can take place in them are summarized at table 1.

Capillary flow is predominant mechanism within the constant drying period, while in the falling drying period, the evaporation – condensation and vapor diffusion are the predominant mechanisms. Effective diffusivity represents an overall mass transport property of moisture, which includes all possible moisture transport mechanisms that are simultaneously controlling the moisture migration process in a material during drying [3, 4].

The procedure for the determination of time dependent $Deff$ presented in [5] is "nearly" the same as ours [3]. Our calculation procedure was applied to determine the time dependent effective diffusion



coefficient using data taken from reference [5] as well as for the data taken from reference [6]. The estimated effective moisture diffusivities were plotted as moisture ratios and are presented at figure 2. It can be seen that the shape of the curves presented at figure 2 are similar to and comparable with the shape of the curve presented in references [5, 6]. The moisture diffusivity profiles shown at fig 1 are also similar to those reported in the literature [7- 9]. It is also very important that all the transition points of the internal mechanisms registered at figure 1 and explained in table 1, are present and can be registered in the same way on figures 3 and 7 reported in references [5] as well as on figures 1 and 3 reported in references [6], regardless of the fact that the calculation method for the determination of time dependent effective diffusion coefficient were different from the method presented in our study [3].

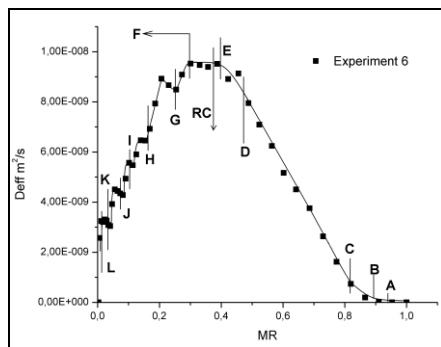


Figure 3. Reference [3].

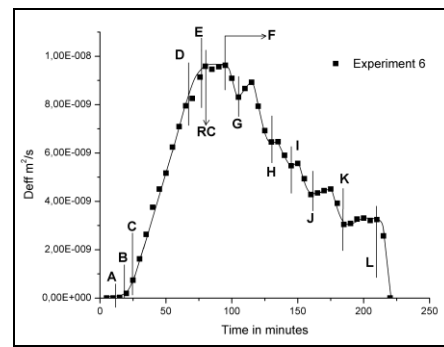


Figure 4. Reference [3].

Figure 1. Typical curves which represents the dependence $Deff - MR$ or $Deff - t$

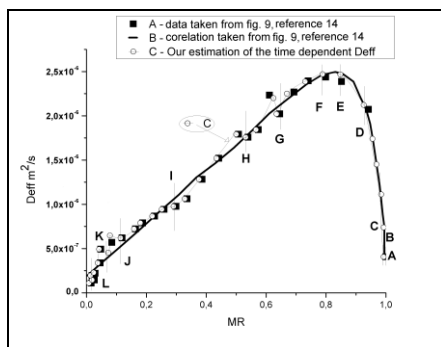


Figure 11. Reference [3].

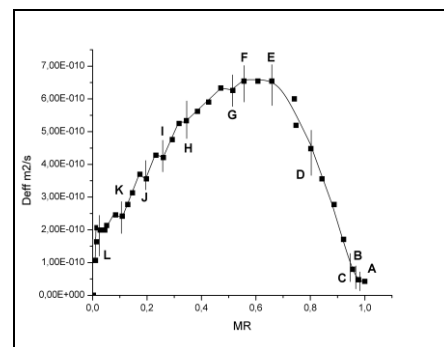


Figure 9. Reference [3].

Figure 2. Estimated effective moisture diffusivities for the data presented in references [5, 6].

Drying is energy intensive process which has a decisive effect on the quality of the clay tiles dried commercially. Escalating energy costs, requirements for eco-friendly and sustainable technologies as well as the rising consumer demand for higher clay tiles quality are the everyday reality in the clay tile production. Industrial drying chambers and drying tunnels are constantly passing the innovation process.

The aim of innovation is to use waste heat from the firing process, shorten the drying time and lower the energy consumption. In order achieve all previously mentioned it is necessary to have a precisely defined drying regime which corresponds with the clay tile raw material. It must be said that there are no widely accepted indicators of innovative performance or common set of indicators to assess the returns on investments. A typical industrial drying regime of clay tiles is presented at figure 3. It can be seen that drying process is not governed isothermally.

The next goal was to create a drying regime which could in advance characterize the real non isothermal process of drying clay tiles. In order to fulfill these objectives the real non isothermal drying regime was obtained by combining five different isothermal drying segments.

Table 1. Possible drying mechanisms according to reference [3].

Drying segment	Transport of liquid water	Transport of vapor	Additional explanation
A B	Capillary pumping flow through the biggest capillaries	/	0A – initial heating AE - constant period FL - falling period
B C	Capillary pumping flow through macro capillaries hydrodynamic flow	/	
C D	Capillary pumping flow through mezzo capillaries Hydrodynamic flow	/	D – “upper critical” point “funicular state” (continuous threads of moisture are present in the pores) Surface is completely wet Front start to recede into body
D E	Capillary pumping flow (from capillaries in funicular state) Hydrodynamic flow liquid diffusion in the pores	hydrodynamic flow	DE – Partially wet surface
E F	Creeping along the capillary when the liquid is in the funicular state or by the successive evaporation – condensation mechanism between liquid bridges.	hydrodynamic flow (difference in total pressure)	F - “lower critical” point - “pendular state” (continuous threads of moisture are not presented in the pores) - “last” wet patches disappeared from the surface
F G	the successive evaporation – condensation mechanism between liquid bridges of pendular water	hydrodynamic flow (difference in total pressure)	
G H	the successive evaporation – condensation mechanism between liquid bridges of pendular water	Stefan Flux (difference in partial pressure) hydrodynamic flow (difference in total pressure)	
H I	The evaporation – condensation mechanism was still active but is decreasing rapidly	hydrodynamic flow (difference in total pressure)	
I J	/	Molecular diffusion	
J K	/	Transition diffusion	
K L	/	Knudsen diffusion	

2. Materials and Methods

Experiments were carried out with the raw material obtained from the factory „Potisije Kanjiža“. Obtained raw material has passed homogenization process in the factory and was ready for the forming process. Laboratory samples 120x50x14 mm were formed in a laboratory extruder "Hendle" type 4, under a vacuum of 0.8 bar.

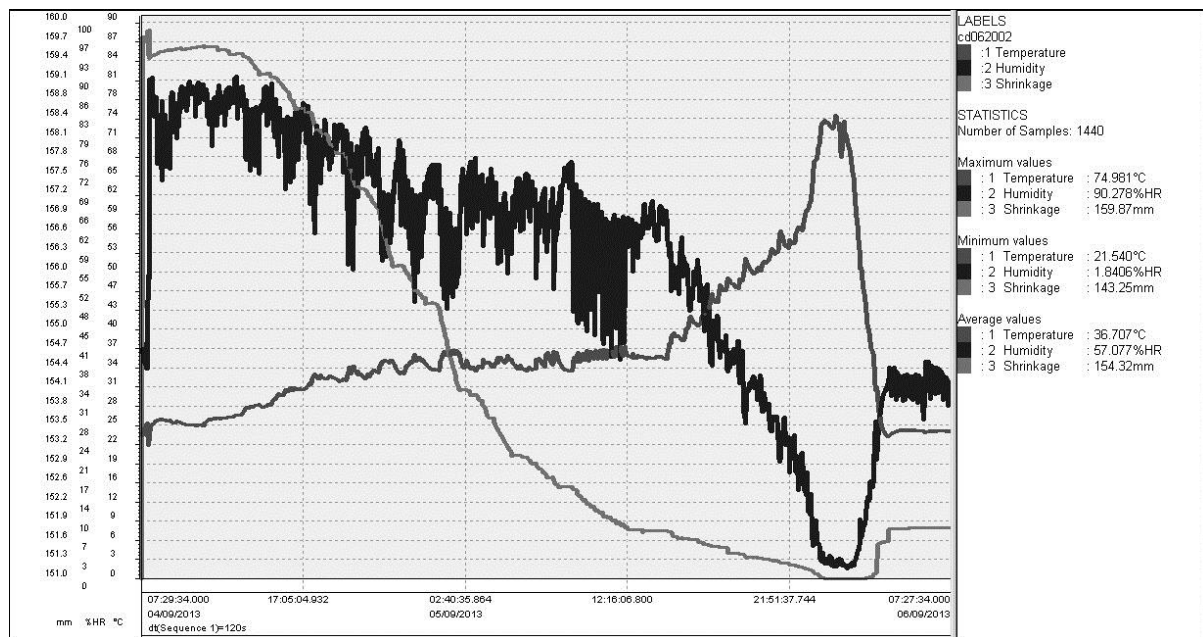


Figure 3. Example of the real non isothermal industrial drying regime.

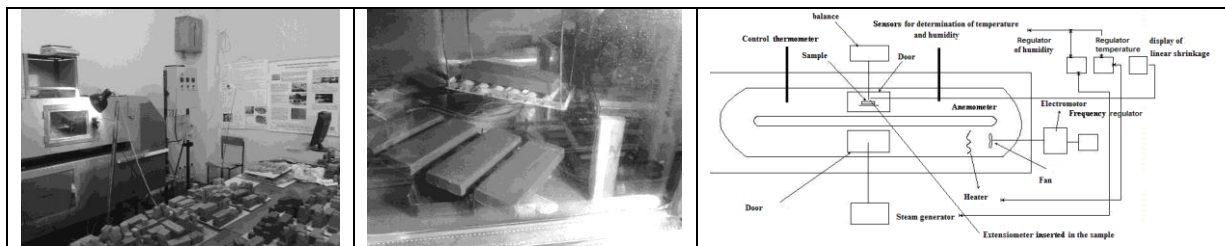


Figure 4. Schematic view of laboratory recirculation dryer.

On prepared clay tiles (samples), in laboratory recirculation dryer, presented at figure 4, under experimental conditions which are presented in table 2, drying kinetic curves were recorded. Technological properties of the raw material during drying and forming process are shown in table 3. In this paper we have used calculation methods previously described in [3, 4].

Table 2. Experimental conditions.

Experiment	Air velocity, W (m/s)	Air temperature, T (°C)	Air humidity, V (%)
1	1	35	75
2	1	45	70
3	1	45	60
4	1	50	60

3. Result and discussion

Drying data obtained, under the experimental conditions presented at table 2 have been simulated using the previously reported variable diffusivity model [3]. Simulated results are presented graphically at figure 5 and figure 6.

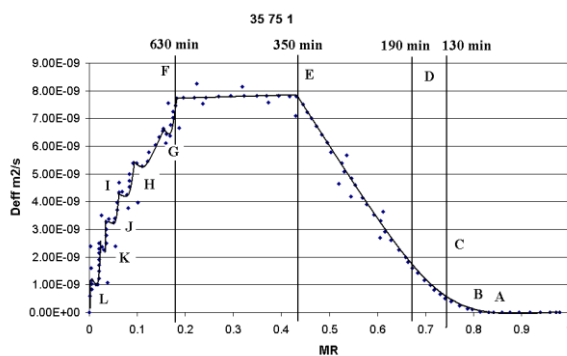
The exact transition points between possible drying mechanisms were detected and are presented at figure 5 and figure 6. It can be seen that the effective diffusivity values are increasing from experiment 1 to experiment 4 while the time to reach the characteristic points is respectively decreasing. This is

expected because the value of the drying air humidity is decreasing from experiment 1 to experiment 4, while temperature is respectively increasing.

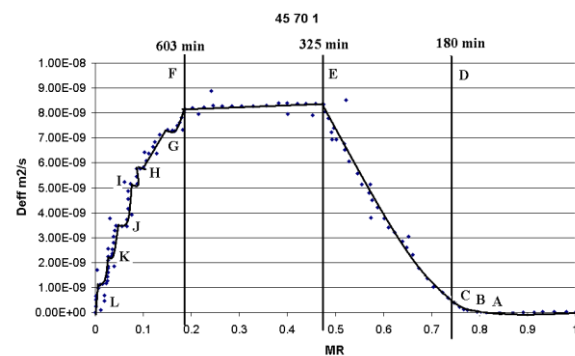
When point E is passed about 90 – 93 % of the shrinkage of the product is over and the clay tile will not crack. Theoretically speaking, when point F is passed and the clay tile is in the funicular state shrinkage of the product is over and the product can not crack. That is the reason why it is very important to know the exact position of the point E. In other words when point E is passed temperature of the drying air has to be increased while simultaneously drying air humidity has to be decreased.

Table 3. Technological properties of the raw material during forming and drying process.

Forming process			Drying process		
The amount of water for forming in (%)	20.94		Shrinkage at critical point (%)	5.69	
Plasticity according to Feferkorn	Coefficient of plasticity	27.5	Water loss at critical point (%)	7.66	
	Plasticity criteria	Good plasticity	Time when first crack is appearing (min)	3.4	
			Drying criteria	sensitive	

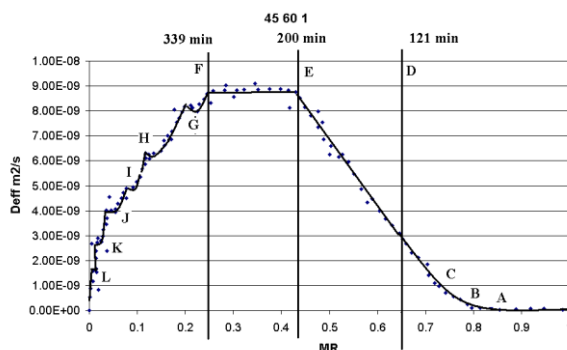


Experiment 1

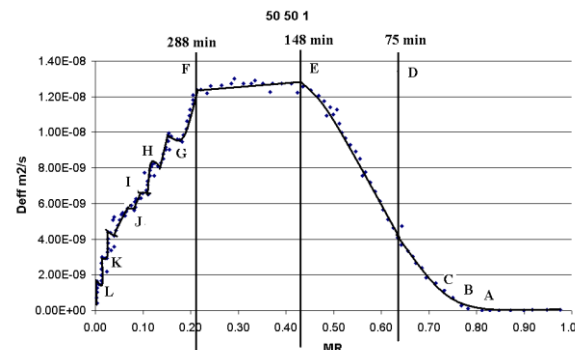


Experiment 2

Figure 5. Estimated effective moisture diffusivity as a function of moisture ratio for experiments 1 and 2.



Experiment 3



Experiment 4

Figure 6. Estimated effective moisture diffusivity as a function of moisture ratio for experiments 3 and 4.

The non isothermal drying process was approximated by 5 segments. In each of these segments approximately isothermal drying condition were maintained. In the first four segments temperature and humidity were maintained as in isothermal experiments and in the fifth segment temperature and humidity were kept at 70°C / 40% respectively.

Duration of the first segment was the same as the duration of the characteristic drying period t_C obtained from the experiment 1 (figure 5), from starting point till point C. Duration of the second segment was the same as the duration of the characteristic drying period t_{CD} obtained from the experiment 2 (figure 5) from point C till point D. Duration of the third segment was the same as the duration of the characteristic drying period t_{DE} obtained from the experiment 3 (figure 6) from point D till point E. Duration of the fourth segment was the same as the duration of the characteristic drying period t_{EF} obtained from the experiment 4 (figure 6) from point E till point F. Duration of the fifth drying segment was one hour. It was obtained experimentally. Previously mentioned drying segments were linked in experiment 5.

The clay tile in experiment five was dried without cracking using the proposed non isothermal drying regime. Dried tile was tested according to the standards EN 1024 in order to see the linearity and planarity coefficient. Results are given in table 4. Tested tile has satisfies regulation of the standard EN 1024 to issues of the linearity and planarity coefficient.

Table 4 Test results according to EN 1024.

Standard SRPS EN 1024		Criteria
Linearity coefficient R (%)	0.14	Allowed deviations of the linearity coefficient: $\leq 1,5\%$ for length $>300\text{mm}$, 2% for length $\leq 300\text{ mm}$
Planarity coefficient C (%)	0.09	Allowed deviations of the planarity coefficient: $\leq 1,5\%$ for length $>300\text{mm}$, 2% for length $\leq 300\text{ mm}$

4. Conclusions

Innovation in drying technologies is continuing over the past three decades, although it has not accelerated because of the long life cycles of dryers and relatively unchanged fuel costs over the past decade. The main goal of innovation in clay tile production is to use waste heat from the firing process, shorten the drying time and lower the energy consumption. Replacements of thermo-technical equipments, better control of drying air parameters during convective drying in old tunnel or chamber drying has been achieved over last 10 years. All these measures are worthless if precise drying regime, which is correlated with the nature of the clay raw material, is not used. Determination of the optimal drying regime can occur without heavy investments of time, manpower and funds only when we are able to use a reliable electronic kit to simulate convective drying in the specially constructed laboratory dryer. This implies that a strong base in fundamental knowledge is necessary to set up and characterize the optimal drying regime. This paper represents a pioneer work in which a non-isothermal drying regime was proposed. It was consisted from five isothermal segments. For the first time the duration of the approximately isothermal drying segments were not specified by experience or by methods trial and error. It was detected from the curves $\text{Deff} - \text{MR}$. Proposed isothermal drying regime was tested. Clay tile was dried without cracks. Dried tile has satisfies regulation of the standard EN 1024 to issue of linearity and planarity coefficient.

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