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Convective heat transfer analysis in aggregates rotary drum reactor

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HIGHLIGHTS

► A thermal and flow experimentation is performed on a large-scale rotary drum.
► Four working points is chosen in the frame of asphalt materials production.
► Evaluation of the convective transfer mechanisms is calculated by inverse method.
► The drying stage is performed in the combustion area.
► Wall/aggregates heat exchanges have a major contribution in the heating stage.

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ABSTRACT

Heat transport characterisation inside rotary drum dryer has a considerable importance linked to many industrial applications. The present paper deals with the heat transfer analysis from experimental apparatus installed in a large-scale rotary drum reactor applied to the asphalt materials production. The equipment including in-situ thermal probes and external visualization by mean of infrared thermography gives rise to the longitudinal evaluation of inner and external temperatures. The assessment of the heat transfer coefficients by an inverse methodology is resolved in order to accomplish a fin analysis of the convective mechanism inside baffled (or flights) rotary drum. The results are discussed and compared with major results of the literature.

1. Introduction

Rotary kiln process is one of the most current industrial stages applied to many products of chemical, food and materials industry including mineral, metallurgical or waste processing. The capability to treat large amount of materials makes the rotary drum as a convenient gas/solid reactor with intensive heat and mass transfer.

The rotary kiln can operate by external heating in the case of organic matter treatment [1], or by internal heating for mineral materials processing. Usually, this latter is designed as a classical furnace where a burner is located at the inlet in order to release sufficient energy for heat treatment. The drying process consists in extracting the moisture content of these materials involving many technologies (atomization, flash dryer, fluidized bed) used in many important manufacturing sectors (minerals, polymers, paper). For road industry, the rotary drum dryer is the most appropriated continuous process in order to reach high aggregates feed rate, and to accomplish successive operations of drying, heating, mixing and coating with bitumen binder for asphalt concrete production.

Academic problem persists in tumbler such as the prediction of particle motion [2] including effect of cohesion, the heat and mass transfer rates [3], and the global internal heat exchanges. These phenomena are crucial in order to enhance heat and mass transfer and globally improve the performance of the rotary drum dryer. Important points were focused upon the interfacial heat transfer phenomena inside particulates rotary kiln. Thammavong et al. [4] described the many experimental results existing in the literature dedicated to the evaluation of the gas/wall transfer coefficient, h_{gw}, and the solid/wall transfer, h_{sw}. Based on the penetration model, many equations have been identified in order to predict solid/wall transfer coefficient in rotary kiln in laboratory tumbler with sand materials.

Wes et al. [5] were the first to introduce a semi-empirical equation from a large amount of data. Schlunder [6] introduces the thickness film gas, χ, to the penetration modelling in order to determine precisely heat transfer through fluidized and porous media. Recently, these approaches have been studied and

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experimentally compared by Herz et al. [7], from several model of the literature [5,8,9]. Presented in Table 1, it appears that the model of Wes et al. (1976) [5] is compatible at low rotational speed ($n < 6$ rpm) while model of Tscheng and Watkinson (1979) [8] is more appropriated at upper rotational speed.

The specific experimental conditions applied to the rotary drum of asphalt plants deserve to reconsider the literature for this kind of application.

2. Hot-mix asphalt reactor: position of the problem

The process consists of mixing mineral aggregates, of mass fraction generally equal to 0.95, and bitumen binder, of mass fraction equal to 0.05, to produce the asphalt mix, which is also called "asphalt concrete". However, the aggregates must be dried and heated prior to mixing in order to obtain satisfactory fluidity (workability) of the concrete. The rotary drum dryer including L-baffle, features a long rotating cylindrical shell slightly inclined to the horizontal, is the most popular equipment in the asphalt industry. In a direct heat rotary dryer, hot gases are supplied by a burner operating in turbulent flow regime through the dryer. These hot combustion gases in turn provide the heat required for vaporization of the water and heating of the aggregates. At the end of the drying and heating steps, the aggregates are in an appropriate condition to be successfully mixed with bitumen until reaching a temperature of asphalt concrete roughly equal to 440 K.

To the best of our knowledge, except few numerical works based on a global analysis [10] or a CFD tool [11], very few previous studies [12] have treated of the heat transfer analysis inside large-scale rotary drum dryer. Despite the size difference between particles and aggregates, the work of Leguen et al. [13] show that the granular mixing in the bulk flow (see Fig. 1) appears similar than particulates laboratory tumbler of the literature [14]. Fernandes et al. [12] used a simplified drying model from an overall coefficient of heat transfer proposed by Miller et al. [15]. Results of this model conduce to a deviation corresponding to 20% compared to the experimental measurements. A better estimation of the heat transfer coefficients would improve this type of drying model.

The present paper proposes to apply an experimental methodology in order to assess the local heat transfer coefficients in large-scale rotary drum dryer during hot-mix asphalt production. Mass flow rates, aggregates/gases temperatures measurements and humidity contents of the aggregates are simultaneously acquired along the tumbler. The external temperature is measured by infrared thermography that is recognized as a promising technique in the non-destructive thermal analysis [16,17]. A physical model based on the heat balance is solved through the wall in order to reach the heat transfer coefficients inside the aggregates rotary drum reactor. This approach is made possible since the thickness of the stainless steel ($e = 8$ mm) is thin enough, satisfying a lumped system analysis, and so the criteria based on the Biot number ($Bi = h.e/\lambda << 1$).

Table 1
Wall to solid heat transfer coefficient used in rotary kiln.

Author	Heat transfer coefficient h_{sw}	Validity domain	
		Particles diameter d_p	Assumptions
Wes et al. (1976) [5]	$h_{sw} = 2k_b(2n/a_b\varphi_0)^{0.5}$ $Nu = 22Pe^{0.5}$	$137 < d_p$ (μm) < 1260	$3.5 < \omega$ (rpm) < 6
Tcheng and Watkinson (1979) [8]	$h_{sw} = 11.6k_b(nR^2/a_b\varphi_0)^{0.3}/l_w$ $Nu = 11.6Pe^{0.3}$		$3.5 < \omega$ (rpm) < 10

Fig. 2 presents the physical model corresponding to the assessment of convective transfer coefficient inner the drum. Its evaluation is calculated from the heat balance in an elementary surface, dS, of length dz of the drum and equal to:

$$dS = 2\pi \cdot r_i \cdot dz \quad (1)$$

It can be written according to the following budget:

$$d\varphi_{\text{int}} = d\varphi_{cond} = d\varphi_{sh} \quad (2)$$

- $d\varphi_{int}$ corresponds to the heat transfer between the multiphases system (including aggregates and freeboard gases) and the inner wall according to the following expression:

$$d\varphi_{\text{int}} = h_i \cdot (T_{iw} - T_g) \cdot dS \quad (3)$$

with h_i, the heat transfer coefficient of the particulates system. T_{iw} and T_g being respectively the inner wall temperature and the gases measured temperature.

- $d\varphi_{cond}$ corresponds to the heat transfer in the thickness of the drum dominated by the axial conductive transfer according to the following expression:

$$d\varphi_{cond} = \frac{\lambda \cdot (T_{ew} - T_{iw})}{\ln (r_e/r_i)} \cdot dS \quad (4)$$

where λ is the thermal conductivity of the steel shell, r_i, the internal radius, r_e, the external radius and T_{ew} the external wall temperature of the rotary drum.

- $d\varphi_{sh}$ corresponds to the heat loss of the wall, given by the following expression:

$$d\varphi_{sh} = \left[h_e \cdot (T_e - T_{ew}) \cdot r_e + \varepsilon_{sh} \cdot \sigma \cdot \left(T_e^4 - T_{ew}^4\right)\right] \cdot dS \quad (5)$$

with h_e, the external transfer coefficient of the rotary drum, T_e the ambient temperature and ε_{sh} the emissivity of the shell.

The external transfer coefficient exerted upon the circumferential length of the drum, L_c, is calculated by a correlation of Kays cited by Labraga and Berkah [18] and given by:

$$Nu = \frac{h_e \cdot L_c}{\lambda} = 0.135 \cdot \left(0.5 \cdot \text{Re}_w^2 + \text{Re}_\infty^2 + Gr\right)^{1/3} \quad (6)$$

with $\text{Re}_\omega = \omega \cdot r^2 / \nu_a$, with ω, the angular velocity of the drum, and ν_a, the kinematics viscosity of the ambient air.

The heat balance conservation through the shell, (1) = (3) and (2) = (1), leads to the elimination of the unknown, T_{iw}, to form a fourth degree polynomial such as:

$$a \cdot T_{ew}^4 + b \cdot T_{ew} + c = 0 \quad (7)$$

with:

$$a = \varepsilon \cdot \sigma \cdot A \cdot (1 + h_i \cdot B)$$

$$b = h_e \cdot A + h_i \cdot B + h_e \cdot h_i \cdot A \cdot B$$

$$c = (1 + h_i \cdot B) \cdot \left(- h_e \cdot A \cdot T_e - \varepsilon \cdot \sigma \cdot A \cdot T_e^4\right) - h_i \cdot B \cdot T_i$$

and