CHEMICAL ENGINEERING RESEARCH AND DESIGN 92 (2014) 80–90

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Mineral wool melt fiberization on a spinner wheel

Brane Širok[a], Benjamin Bizjan[a], Alen Orbanić[b], Tom Bajcar[a,*]

[a] University of Ljubljana, Faculty of Mechanical Engineering, Askerceva 6, 1000 Ljubljana, Slovenia
[b] Abelium d.o.o., Kajuhova ulica 90, 1119 Ljubljana, Slovenia

ABSTRACT

In this paper, the formation of mineral wool fibres has been studied on a real industrial production process. Parametric dependence of the melt film structural dynamics on the spinner wheel rotational frequency was investigated. The results presented indicate the presence of the melt instability that is formed as a complex quasi-periodic oscillation of the structures on the melt film surface. In addition to the melt oscillations which coincide with the rotating frequency of the spinner wheel and its higher harmonics, aperiodic melt structures also appear. These structures result from the Taylor instability, which is inherent to liquid movement and is one of the basic mechanisms of the formation of melt ligaments that solidify into mineral wool fibres. Based on the results, a phenomenological model for structural instability as a function of the wheel rotational frequency was formed, indicating a characteristic influence of melt film dynamics on the fibre formation and indirectly, on the quality of the end product.

Keywords: Mineral wool; Fluid mechanics; Fibres; Computer-aided visualization; Experimental modelling

1. Introduction

Mineral wool is a general term for different types of inorganic insulation materials such as the rock-, glass- and ceramic wool. Most common input raw materials in mineral wool production are basalt, diabase, dolomite, granite, etc. The fibres form a homogenous anisotropic structure that has excellent sound and heat insulation properties.

Among the mineral wool production methods, melt fiberization on a spinner wheel is used most commonly (Širok et al., 2008). Mineral wool melt with the temperature of approximately 1450 °C exits the cupola furnace through the siphon into the feed channels above the first spinner wheel. The melt string falls onto the wheel and is drawn into motion as a result of its viscosity, forming a thin radial film. Fibres form from the film and are transported by the blow-in flow into the wool chamber where a primary layer of mineral wool is formed.

Fibre formation from melt film on the spinner wheels is one of the most important but least understood process phenomena in mineral wool production. Most of the research so far has been focused on the relation between the spinner input parameters (rotational frequencies of the spinner wheels, melt string impingement point, melt rheological properties, velocity of the blow-in flow, etc.) and the mineral fibre properties, such as the fibre thickness, length and spatial distribution and the fraction of unfiberized material (pearls). For example, Širok et al. (2008) developed an accurate statistic multiple regression model for the prediction of fibre thickness. While this type of analysis can give reasonably accurate results on the integral level of the manufacturing process, it does not provide any information about the fiberization mechanism on the micro scale. A better understanding of the fiberization process could lead to further improvements in the efficiency and control of mineral wool production. Nevertheless, due to harsh conditions, including very high temperatures and multiphase flows, choice of experimental methods for melt fiberization analysis on the spinner wheels is very limited. For this reason, the understanding of mineral wool fiberization is based primarily on the theoretical models.

According to Eisenklam (1964), the most probable fibre formation mechanism is by hydrodynamic instabilities that occur on the rotating melt film. As a result, liquid ligaments form from the melt surface and solidify into the mineral wool fibres. Initial fibre formation and motion is caused by the forces of inertia, viscous resistance and surface tension whereas the fibre solidification also significantly depends on the

* *Corresponding author*. Tel.: +386 1 4771422; fax: +386 1 2518567.
E-mail address: tom.bajcar@fs.uni-lj.si (T. Bajcar).
Received 30 November 2012; Received in revised form 10 June 2013; Accepted 12 June 2013
0263-8762/$ – see front matter © 2013 Published by Elsevier B.V. on behalf of The Institution of Chemical Engineers.
http://dx.doi.org/10.1016/j.cherd.2013.06.014

Nomenclature

A	grayscale level (brightness) of an 8-bit image
a	fluctuating component of grayscale level
B	melt film width on a spinner wheel (m)
D	diffusivity (m^2/s)
f_0	spinner wheel rotational frequency (Hz)
f_s	sampling frequency of a spatial series (m^{-1})
h	melt film radial thickness (m)
h_p	pixel size (m/pixel)
k	wave number
$\dot{m}$	melt mass flow (kg/s)
N	melt concentration
R	spinner wheel radius (m)
Re	Reynolds number
Δt	image sampling time (s)
s	spacing between perturbations/ligaments on melt film surface (m)
t	time (s)
v	absolute velocity vector (m/s)
v_0	tangential velocity of the spinner wheel (m/s)
v_f	average absolute velocity of melt film surface (m/s)
v_v	average absolute velocity of fibres in the region of interest (m/s)
We	Weber number

Greek letters

γ	surface tension (N/m)
λ_m	wavelength of the most unstable perturbation on the melt film surface (m)
λ_{CO}	cutoff wavelength (m)
μ	dynamic viscosity (Pa s)
ξ	dimensionless disturbance growth rate
ρ	melt density (kg/m^3)
ω	spinner wheel angular velocity (rad/s)

thermodynamic properties of the melt and the aerodynamic properties of the blow-in flow (Blagojević et al., 2004).

In the present study, the influence of the spinner wheel rotational frequency on the melt and fibre flow dynamic properties was investigated by obtaining photos with a high-speed camera and processing them numerically. The analysis of the melt film flow characteristics on the spinner wheel was based on the comparison of the typical distances between the melt surface perturbations, acquired from experimental data, and those calculated from the known phenomenological models of liquid ligament formation (Hinze and Milborn, 1950; Liu et al., 2012). In addition, melt and fibre velocities were calculated using image analysis software. A new phenomenological model for spacing between the ligaments on the melt film was proposed.

2. Experimental set-up

Experiments were performed on a four-wheel spinner (Fig. 1) that was a part of an industrial mineral wool production line. The region of interest was narrowed to the first spinner wheel where three distinctive regions were present, marked as (A), (B) and (C) in Fig. 1. Region (A) represents the flow of the melt string onto the wheel to the impingement point. Melt flow dynamics has a significant effect on melt film formation and consequently, fiberization process quality. Region (B) is in an area on the wheel edge where a thin melt film is formed. On the film surface, initial fiberization occurs, resulting in liquid ligament formation. Region (C) denotes the area immediately above the wheel where the partly formed fibres move towards the blow-in flow. In this paper, regions B and C were studied.

Using a high speed digital camera (Fastec HiSpec4 2G Mono with Nikon 50 mm f1:1.2 lens), 8-bit grayscale images of the selected regions of interest were recorded at 18,660 frames per second with a resolution of 128 × 328 and a pixel size of 0.37 mm. The experimental set-up is shown in Fig. 2.

Rotational frequency of the spinner wheel was varied in the 100–117 Hz range as given in Table 1. At every frequency step (1–6), two sets of 2500 images were recorded. The region of interest used for the first set of images was a near-vertical melt film segment on the spinner wheel (Figs. 1 and 8) and the exposure time was set to 6 μs. The region of interest for the second set was an area at the edge of the wheel where the fibre flow was visible, with a 16 μs exposure time. In both cases, the camera was placed at an angle of approximately 45° with respect to the spinner wheel rotation axis.

Other process parameters, including the temperature, mass flow and chemical composition of the melt, were kept constant for all experiments. Melt mass flow was 5 t/h (1.39 m/s).

Table 1 – Variation of the spinner wheel rotational frequency.

Experiment No.	1	2	3	4	5	6
Rotational frequency, f_o (Hz)	117	113	110	107	103	100

3. Mechanism of mineral wool fiberization

Eisenklam (1964) studied inviscid liquid disintegration by ligament formation from spinning discs and cups on a theoretical basis. Hinze and Milborn (1950) investigated ligament formation experimentally for low and moderate viscosity Newtonian fluids and similar results were obtained regarding the spacing between liquid ligaments on the rim of the disc. The authors also discovered that at a constant flow rate, ligaments are only formed at moderate rotational frequencies, with direct drop and sheet formation present at slower and faster rotation, respectively. The theory can also be applied to the mineral wool fiberization as the mineral wool melt behaves as a Newtonian fluid at the temperature of initial ligament formation from the melt film (1200–1300 °C) (Shelby, 1997; Širok et al., 2008). As the melt ligaments cool down, the fluid becomes non-Newtonian and gradually, solidification occurs.

In the present study, however we only investigated the liquid ligament formation phase. Eisenklam explained this phase by hydrodynamic instabilities that occur on the surface of the liquid. A string of melt flows vertically onto the rotating disc where it is drawn into motion by the viscous resistance of the melt. There are several types of instabilities occurring on the melt layer. As a result of velocity slip on the interface of melt and air, Kelvin–Helmholtz instabilities are generated which, together with some other phenomena such as unsteady flow within the melt string and wheel vibrations, cause perturbations on the surface of melt layer to appear. The main source of instability however, making these perturbations much stronger, is the Rayleigh–Taylor instability (Taylor, 1950), which is caused by the centrifugal force accelerating the