Chemical Engineering Science 105 (2014) 143–154

Contents lists available at ScienceDirect

Chemical Engineering Science

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

The formation and breakup of molten oxide jets

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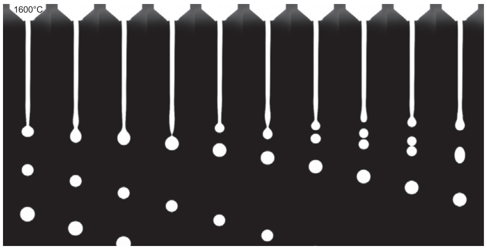
HIGHLIGHTS

- High-speed images of natural breakup of slag jets at 1600 °C at different flow rates.
- The jet length is analysed as a function of time and is normally distributed.
- The jet length is predictable taking the instability wave Reynolds number into account.
- Short jets break up in a regular manner and produce narrow drop size distributions.
- Drop size decreases for higher flow rates and approaches Rayleigh mode.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 August 2013
Received in revised form
8 October 2013
Accepted 15 October 2013
Available online 25 October 2013

Keywords:
Slag
Capillary breakup
Surface tension
Droplet formation
Jet

ABSTRACT

Experimental investigations on the capillary breakup of jets of molten oxides (slags) at high temperatures in an inert atmosphere are presented in this paper. The (in)stability of ligaments, threads, or jets of metallurgical slags is of importance in many heat and mass transfer processes related to high-temperature metal production, and aftertreatment of slags as currently investigated in the dry slag granulation process. In order to quantify the dynamic disintegration process of slag jets into droplets, a three-zone high-temperature furnace with maximum temperatures of 1750 °C and optical access was built. In the present study, a molten synthetic calcia/alumina slag at 1600 °C was used to form jets of 1 mm in diameter at different flow rates. The various phenomena of jet formation, appearance of instability waves, jet disintegration and droplet detachment were captured using a high-speed camera. The jet length distribution was calculated and compared with predictions. A Fast Fourier Transform of the temporal development of the jet length was also performed. The jet length showed good agreement with empirical correlations if the instability wave velocity is used in the definition for Reynolds and Weber number. The size distribution of the formed droplets was investigated and compared to theoretical predictions. For higher flow rates, the main peak agrees very well with theoretical equations. For low flow rates near to transition to the dripping regime, short jets formed in a highly repetitive manner. The drop size distribution was found to be very narrow with a mean diameter according to Tate's law taking into account a Harkins and Brown correction factor.

1. Introduction

The (in)stability of liquid jets is a classical problem in fluid dynamics and has been studied since the 19th century (Amini and Dolatabadi, 2010). Since then, an overwhelming amount of work – both experimental and theoretical – has been done to reveal the fundamental mechanisms of disintegrating jets. The fields of application are equally manifold ranging from practical everyday life applications to industrial processes, such as follows:

- Liquid/liquid processes: liquid extraction columns (Grant and Middleman, 1996), spray columns, injection of dispersed phase

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http://dx.doi.org/10.1016/j.ces.2013.10.030

into mixing vessels in mixer-settler apparatuses, fibre spinning operations or liquid/liquid jet reactors (Skelland and Walker, 1989), etc.
- Gas/liquid processes: fuel injection technology, solder spheres (Shimasaki and Taniguchi, 2011), irrigation systems, spray-drying technology (Eggers and Villermaux, 2008), spray forming and coating (Passow et al., 1993; Srinivasan et al., 2011), drop on demand technology (Basaran and Suryo, 2007), etc.
- Everyday life environment: showers, sinks, pharmaceutical sprays (Eggers and Villermaux, 2008), garden hoses, hair sprays (Birouk and Lekic, 2009), etc.

The formation and breakup of jets is also important for metal production, for example steelmaking processes such as the Basic Oxygen Furnace (BOF) and the Electric Arc Furnace (EAF) (Alam et al., 2009). Gas jets at supersonic speed ($M>1$) are blown into the bath and generate jets and filaments of hot liquid which eventually break into droplets (so-called splashing). Bubbles of inert gases are used to enhance the distribution of alloys in the ladle. Bubbles may escape towards the gas/liquid interface of the melt and may eject as jets which then break up into droplets. Given a certain kinetic energy, this may also cause a slag/metal dispersion resulting in entrapment (Hahn and Neuschütz, 2002; Han and Holappa, 2003).

During the last decade, efforts were increased around the world to recover the heat from slags by rotating atomisers. In the most common configurations, molten slag falls onto a spinning disc (Nexhip et al., 2004; Xie et al., 2010; Yoshinaga et al., 1982) or a cup/cylinder (Kashiwaya et al., 2010a, 2010b; Liu et al., 2011; Pickering et al., 1985). Centrifugal forces transport the liquid to the edge of the rotating device where it forms droplets, ligaments, or liquid sheets. The breakup in the ligament regime produces a narrow drop size distribution which is important to control the heat transfer and to avoid particle agglomeration.

A similar approach is pursued for Liquid Droplet Heat Exchangers (LDHX) (Bruckner and Mattick, 1983; Bruckner, 1985; Thayer et al., 1983). In one concept, the LDHX is embedded in a solar thermal power plant process. Instead of molten salts, the use of a synthetic slag (which is more temperature stable and relatively cheap) is proposed to increase the process effectivity. Molten slag enters a vertical column via an array of nozzles. Jets form which later disintegrate into desirably uniform-sized droplets. During their fall, the droplets solidify and transfer heat to a counter-current gas stream. The solid particles can eventually be fed back to the heat source. However, little is known about the behaviour of slag jets at high temperatures, and how to control the drop size distribution from slag jets. Accordingly, no LDHX based on metallurgical slags has been built so far, hence fundamental experimental studies are necessary.

1.1. Problem formulation

The breakup of liquid jets at ambient temperatures has widely been studied. Metal jets at moderate temperatures have also been investigated to a certain degree in terms of breakup, for example in high-precision solder printing technology (Liu and Orme, 2001; Orme et al., 2000), surface tension measurements of Sn/Pb jets (Bellizia et al., 2003; Howell et al., 2004), or influence of oxygen on the breakup of metal jets (Artem'ev and Kochetov, 1991; Lai and Chen, 2005). However, little is known about the fluid dynamic stability behaviour of molten slag jets. Metals have a high surface tension but usually a relatively low viscosity, whereas slags are both high surface tension and high viscosity liquids. Moreover, the viscosity strongly depends on temperature. The liquidus of common molten oxides such as calcia/silica/alumina strongly depends on the composition and may easily exceed 1400 °C (Ohno et al., 2011; Slag Atlas, 1995). Experimental investigations at these temperatures are time consuming, expensive, and demanding, especially in terms of material selection and apparatus design.

To the authors' knowledge, few experimental studies on the breakup of slag jets at high temperatures have been published so far. Benda (1983) performed studies in the framework of the LDHX concept. The focus was on the production of uniformly sized droplets from disintegrating jets of molten slags. Some experimental studies were performed in a furnace with and without external excitation. A few photographs show slag jets and proper and improper jet disintegration, but quantitative analysis was restricted to the evaluation of drop size distributions from quenched slag globules. Overall, the experimental results demonstrated the applicability of known theoretical prediction methods to a certain degree. However, many questions remained unanswered, especially those concerning the dynamics of jet formation and breakup.

The problem of jet stability is highly complex due to a large number of parameters, such as – but not limited to – nozzle or capillary design, the thermophysical properties of the fluids involved, the interplay of inertia, viscous, capillary and aerodynamic forces, as well as mass transfer and surfactant adsorption (Amini and Dolatabadi, 2010). In most published experimental studies, a controlled jet destabilisation by external disturbances is favoured, since a periodic state may be reached in which only few measurement points are required to measure the growth rate of the instabilities. Mostly, these controlled breakup experiments have been used to validate the available theoretical models of jet stability by comparing experiments with the theoretical dispersion curve (Blaisot and Adeline, 2000).

Non-controlled breakup is also of interest, for example in engine injection or the aforementioned spinning disc/cup techniques. Even in an ambient temperature environment, only few experiments on free falling jets have been reported, see references cited in Blaisot and Adeline (2000). In natural mode (i.e. natural breakup: without any deliberate external excitation applied to the jet), a jet is subject to fluctuations in space and time and shows transient behaviour, as will be shown in the present study on natural breakup of molten slag jets.

1.2. Scope of the present work

The aim of the present study is to investigate the formation and breakup of jets of molten oxides, namely a synthetic calcia/alumina slag. This study focusses on jet formation, appearance of capillary waves, unbroken jet length (and its distribution), and frequency distribution of the droplet sizes formed by jet disintegration. Natural jet breakup was explored in detail for different operating conditions (i.e. different flow rates or Reynolds numbers) at 1600 °C in an inert environment. A high-temperature three-zone furnace with optical access was used and the phenomena were video recorded by means of a high-speed camera. Automated image analysis was used to examine the massive amount of recorded data. The discussion highlights the degree of predictability of the relevant breakup phenomena by theoretical and empirical equations.

2. Material and methods

The experimental setup consisted of four major components, see Fig. 1: (1) a 3 zone electrically heated tube furnace with a 700 mm heated zone (Tetlow Kilns & Furnaces Pty Ltd Victoria, Australia); (2) a 99.8% high-purity alumina cross tube assembly for optical access and atmosphere control (McDanel Advanced Ceramic Technologies, Pennsylvania, USA); (3) (a–f) a droplet generating device (Mersen Oceania Pty Ltd.) in combination with a back-pressure system; and (4) a Phantom v3.11 high-speed camera