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Use of concentrated radiation for solar powered glass melting experiments

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Abstract

To investigate the feasibility of using concentrated solar radiation to provide process heat for glass production, a high flux solar simulator was used to melt glass forming batches. Initial experiments involved melting various glass forming batches which demonstrated that rapid and full conversion of the crystalline raw materials into an X-ray amorphous vitreous state was possible. A pure silica batch produced an X-ray amorphous product but it was not possible to refine the melt in these exploratory tests. A powdered, ternary soda–lime–silica (SLS) glass forming batch melted vigorously, with rapid gas removal, resulting in a completely transparent glass. Industrial SLS pellets were subsequently used in semi-continuous melting experiments, whereby the batch was intermittently fed into the melting zone while the beam was kept on. Additional secondary heating and insulation around outlet of the melting zone was required to achieve a semi-continuous flow of molten glass to an output crucible.

Keywords: Concentrated solar thermal; Glass production; High flux solar simulator; High temperature melting

1. Introduction

Glass manufacture is a highly energy intensive process, requiring primarily, high temperature process heat, usually provided by burning fossil fuels. The most common type of glass produced is soda–lime–silica (SLS); this consists of three main components: silica sand, which forms the glass network; sodium oxide, a network modifier, usually supplied as sodium carbonate (soda ash), which reduces the temperature at which a melt is formed; and calcium oxide, also usually supplied as a carbonate which improves the chemical stability of the glass produced. Other more minor components are also added to commercial melts, either deliberately or as unavoidable components in the raw materials. The theoretical energy required to convert these raw materials into glass is around 2.7 GJ/t (Trier, 1987a; Scalet et al., 2013). This theoretical value is based only on the chemical heat of reaction plus the enthalpy changes associated with heating up the raw materials ('batch') and the gas produced, from ambient temperature to the generally assumed melting temperature of 1500 °C. However, in practice, significant additional energy is required to overcome heat losses associated with maintaining the glass melt at temperature to enable homogenisation and bubble removal (fining) to occur, in order to produce the required high quality products expected by the modern consumer. This real energy consumption for modern industrial glass melting, with typical production in the order of hundreds

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of tonnes per day (tpd), can vary from 3.5 to 40 GJ/t (Scalet et al., 2013) depending on furnace design and scale, with larger furnaces generally being more efficient.

Environmental degradation and depletion of natural resources necessitates a shift towards more sustainable energy sources for large scale and continuous industrial processes such as glass manufacture. Solar energy is virtually unlimited and can be concentrated to directly provide high temperature process heat. Use of concentrated solar radiation to provide process heat for industry has so far been primarily been limited to low–medium temperature processes (Kalogirou, 2003; Mekhilef et al., 2011). A major part of the research into the use of concentrated solar radiation at very high temperatures has been motivated by the desire to generate high energy density thermochemical energy storage systems (see e.g. Diver et al., 1992; Kodama, 2003; Wieckert et al., 2007; Neises et al., 2012; Martinek and Weimer, 2013; Tescari et al., 2013), and the solar upgrading of carbonaceous materials (Zgraggen et al., 2007; Rodat et al., 2010; Piatkowski et al., 2011). These reaction schemes usually involve solar heating of combinations of gaseous and solid reactants to generate gaseous and solid products such as the two step water and CO_2 splitting reactions involving intermediate metal oxides to generate hydrogen and/or synthesis gas (Steinfeld, 2005; Meier and Steinfeld, 2012; Villasmil et al., 2014; Neises et al., 2012).

Significant research work has also been devoted to the use of concentrated solar radiation for substituting fossil and electrical energy in energy intensive commodity production (Meier and Steinfeld, 2012). This includes production of lime from limestone (Meier et al., 2005), melting of aluminium from aluminium scrap (Funken et al., 2001) and recovery of zinc from zinc containing materials (Schaffner et al., 2003; Tzouganatos et al., 2013). Very few activities have been reported aiming in producing a viscous high temperature fluid as in glass melting. Felix Trombe (1954, 1961) conducted a series of experiments melting high temperature refractory materials, including use of a 1 MW solar furnace to fuse hundreds of kilograms of silica sand in a rotary furnace. However the material produced was opaque, inhomogeneous and with too high viscosity for any useful forming processes. This was probably due to the very high temperatures needed to enable silica to be fluid enough for easy bubble removal which would be a challenge for the furnace refractories.

This paper outlines initial research which aims to investigate the feasibility of using concentrated solar radiation to provide a sustainable source of process heat for glass manufacture. In particular, a high quality, transparent glass with minimal bubble content and sufficient fluidity for forming processes is required. There are several motivations to justify research into the use of solar energy to manufacture glass:

1. The major environmental challenges for glass industry are energy consumption and emissions to air from combustion of fossil fuels and from high temperature oxidation of atmospheric nitrogen i.e. sulphur dioxide, carbon dioxide, and nitrogen oxides (Scalet et al., 2013). Replacing fossil fuel combustion with concentrated solar radiation to provide the process heat for glass melting, directly addresses some of these issues, although the use of carbonate raw materials means that not all CO_2 emissions can be readily prevented.
2. In certain developing countries, such as The Gambia, sufficient infrastructure for conventional industrial glass production facilities does not exist while solar energy and glass making grade silica sand are abundant (International Business Publications, 2011). In such situations, solar powered glass manufacture could enable the sustainable use of local resources to meet local demands.
3. In the future, it is envisaged that solar powered glass production could enable in-situ production of the glass elements (mirrors or lenses) required for new Concentrated Solar Power (CSP) plants in remote sandy desert regions, similar to the “Sahara Solar Breeder” concept set out by Stambouli and Koinuma (2012). This could enable significant savings because currently the cost of these glass components alone account for around 6.1–8.4% of the total cost of a CSP plant (Kolb et al., 2011; IEA-ETSAP and IRENA, 2013). Also there could be additional cost savings associated with the logistics of transporting the heavy, fragile glass components, since around 12 thousand tonnes of glass is required in building a typical 100 MW CSP plant (Müller-Steinhagen, 2009).
4. NASA (Ho and Sobon, 1979) considered the use of concentrated solar radiation for in-situ glass production of glass from lunar based materials. Such research is motivated by the extremely high cost of transporting materials from earth, the abundance of silicate raw materials on the moon which could be used to make glass and the versatility of glass such as its ability to be drawn into fibres for structural and communications applications.

Glass melts exhibit very complex and non-linear thermodynamic/optical properties, that depend on composition, temperature and redox state (Prokhorenko, 2005), which vary significantly in time and space in a furnace. A substantial body of literature exists relating to these properties with respect to heating in conventional fossil fuel fired furnaces (Pye et al., 2005). However, extrapolating this available data to predict results for the case of heating with solar radiation is difficult because:

(1) The most commonly assumed regime in mathematical modelling of heat transfer phenomenon in glass melting furnaces is the ‘optically thick limit’ (Chaudhary, 1985; Chaudhary and Potter, 2005). This basically assumes that the radiation from the heat source is rapidly absorbed/attenuated by the glass melt. Comparison of the spectral power distribution of solar radiation (approximated by a 5505 °C black