Renewable and Sustainable Energy Reviews 37 (2014) 480–501

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Indium alloy-sealed vacuum glazing development and context

Yueping Fang [a,*], Trevor J. Hyde [a], Farid Arya [a], Neil Hewitt [a], Philip C. Eames [b], Brian Norton [c], Seth Miller [d]

[a] School of the Built Environment, University of Ulster, BT37 0QB Newtownabbey, Northern Ireland, UK
[b] Centre for Renewable Energy Systems Technology, University of Loughborough, Loughborough, UK
[c] Dublin Energy Lab, Dublin Institute of Technology, Dublin, Ireland
[d] EverSealed Windows, Inc. 1999 Interlocken Drive, Evergreen, CO 80439-8952, USA

ARTICLE INFO

Article history:
Received 19 September 2013
Accepted 11 May 2014

Keywords:
Vacuum glazing
Finite element model
Finite volume model
Low-emittance coating
Triple vacuum glazing
Hybrid vacuum glazing
Electrochromic vacuum glazing

ABSTRACT

Vacuum glazing consists of two parallel glass sheets with a narrow vacuum gap in between. The sheets are separated by an array of support pillars under the influence of atmospheric pressure imposed on the external surfaces of the two glass sheets. The vacuum gap sealed by a sealant (either solder glass or indium alloy) minimizes the air heat conduction and convection across the glazing. One or two high performance low emittance (low-e) coatings deposited on the internal surface(s) within the vacuum gap reduces the radiative heat transfer to a very low level. The heat transmittance of 0.80 W m^{-2} K^{-1} and 0.86 W m^{-2} K^{-1} at the central area of vacuum glazing with two low-e coatings and support pillars of 0.25 mm and 0.4 mm in diameter were achieved and experimentally characterized using the guarded hot box calorimeters by the University of Sydney and the University of Ulster, respectively. If combined with solar control glazing such as electrochromic (EC) glazing, it has a great potential to significantly reduce the load of heating in winter and cooling in summer and to provide thermal comfort for the occupants. If combined with the third glass sheet forming a gas filled or second vacuum gap, the heat transmittance will be further reduced. In this work, the basic characteristics and fabrication process of vacuum glazing are reviewed. The potential performance of vacuum glazing, EC vacuum glazing and other hybrid vacuum glazing with second either gas filled gap or vacuum gap are presented.

Contents

* Corresponding author. Tel.: +44 2890366808; fax: +44 2890368239.
E-mail addresses: fangyueping@hotmail.com, y.fang@ulster.ac.uk (Y. Fang).

http://dx.doi.org/10.1016/j.rser.2014.05.029
1364-0321/

1. Introduction

Among all building fabric components, usually windows exhibit the worst thermal performance since they employ glass panes to allow sunlight to get in and occupants to view the outside. Vacuum glazing comprises two sheets of glass coated with low-e coatings, separated by arrays of support pillars to counteract atmospheric pressure. Heat loss through the windows occurs in three ways: conduction, convection and radiation. The low-e coatings reduce radiative heat loss to a very low level and the vacuum space (<0.1 Pa) between the two glass sheets eliminates heat conduction and convection. The thermal transmittance, *U*-value, of vacuum glazing is one third of that of a typical gas filled double glazing.

Vacuum glazing was first proposed by Zoller in 1913 with a patent granted in 1924 [1]. Since 1913, many patents [2–22] have been published on this topic. Only recently successful fabrication of vacuum glazing has been reported [23–27]. In the 1980s, Benson and his group at the National Renewable Energy Laboratory in Colorado, U.S.A. published two conference papers [28,29], a patent [14], and a series of reports [28–30]. However, this group did not succeed in fabricating a durable vacuum glazing with good thermal performance. Benson's group used a laser to fuse two sheets of glass together within a vacuum chamber to form a periphery edge seal for the vacuum gap. Although the edge seal was formed successfully, the vacuum level achieved was not low enough to achieve a thermal transmittance less than 1.0 W m^{-2} K^{-1}. The first reported successful production of vacuum glazing was in 1989 from the University of Sydney (USD) [31]. Since that time, many samples of vacuum glazing with an air-to-air, center-of-glazing thermal transmittance *U*-value of 0.8 W m^{-2} K^{-1} have been produced at the USD using a solder glass edge sealing technique [32]. This system has been commercialized by Nippon Sheet Glass Co. Ltd. in Japan under the brand name of “SPACIA”. More recently a Chinese company Beijing Synergy Vacuum Glass Technology Co., Ltd. has commercialized vacuum glazing using different types' solder glass, but no formal paper was seen on an academic journal yet.

A different fabrication method of vacuum glazing using a indium alloy edge seal technique was developed at the University of Ulster (UU); vacuum glazing samples incorporating two *K*-glass [33] sheets were produced with the center-of-glazing *U*-value of 0.86 W m^{-2} K^{-1}, and significant work done on different aspects of vacuum glazing including thermal characterization, thermal ageing tests, thermal behaviour modelling [24–27,34–43].

The key difference between the two fabrication methods developed by the Sydney and the Ulster group is the sealing techniques used to join the two glass panes. The Sydney group use solder glass (melting point of about 450 °C) to seal the vacuum gap which has been proved to work well. But at temperatures of about 450 °C, many soft low-e coatings and tempered glass will be degraded. Nowadays in many jurisdictions for a range of contexts, it is mandatory to use tempered glass in buildings; additionally due to its high mechanical strength, using tempered glass in vacuum glazing makes it possible to increase the pillar separation which leads to a reduction in the heat conduction through the pillar array. The Ulster group has successfully fabricated vacuum glazing samples using indium alloy as a sealant, the process developed is carried out at a low temperature (less than 200 °C). Since a variety of soft low-e coatings and tempered glass can withstand these temperatures (less than 200 °C), the indium alloy based sealing technique has an advantage over the solder glass technique in terms of achievable performance.

Significant theoretical and experiment research into the design and performance of low temperature sealed vacuum glazing was performed by the Ulster group. The Ulster group also developed a finite volume model to calculate the thermal performance of vacuum glazing with various frames, low-e coatings, glazing size, glass thickness and solar insolation [34–42] and the predictions were experimentally validated [39–42]. Optimization of vacuum glazing design was theoretically and experimentally undertaken. A guarded hot box calorimeter was developed to characterize the thermal performance of vacuum glazing. A method for estimating the vacuum level was developed by comparing the measured and simulated glass temperature profiles [35,45]

Within recent 10 years, the companies Guardian, EverSealed Window Inc., and a German group Grenzebach GmbH tried to use either a strip of metal or very thin stainless steel foil as flexible edge seal using ultrasonic bonding to adapt the extreme weather. The stress at the edge area of glass panes caused by the bonding between the flexible edge seal and glass panes is much smaller than that when using either solder glass or indium alloy edge seal. However no successful samples were reported yet to date.

2. Construction and fabrication of a functioning vacuum glazing

Fig. 2.1 shows a schematic diagram of the vacuum glazing developed at the USD. The vacuum glazing was made of two sheets of soda lime glass with a thickness of 3 or 4 mm. The inner surface of one or both sheets may be coated with a transparent low-e coating. Pyrolitically deposited “hard” coatings include