Nuclear Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Designing a high temperature high pressure mesh sensor

John Kickhofel *, Jiaming Yang, Horst-Michael Prasser

ETH Zurich, Laboratory of Nuclear Energy Systems, Switzerland

A R T I C L E I N F O

Article history:
Received 16 February 2017
Received in revised form 14 July 2017
Accepted 17 July 2017
Available online xxxx

Keywords:
Wire-mesh sensor
Two-phase flow
Turbulent mixing
Electrode mesh
Flow conductivity

A B S T R A C T

State-of-the-art turbulence models are expected to accurately predict flow behavior in a wide range of geometries and flow conditions for a wide range of fluid properties. These models rely on accurate time resolved measurements of scalar and vector flow variables. One such measurement technique for obtaining a high density of flow field variables with high time resolution is in the form of electrode-mesh sensors (WMS) which measure the local instantaneous electrical conductance of a flow at a large number of positions, typically in the cross-section of a conduit at frequencies up to 10 kHz. Extensive studies on single and multiphase flows have been carried out with mesh sensor technology in the past 15 years, often focused on flows directly related to nuclear power generation. However, essentially all of these experiments have taken place at low temperatures (<100 °C) and pressures.

A new mesh sensor construction has been designed at the ETH Zürich for operation in high temperature and pressure pipelines by implementing novel materials, assemblies and a new sealing methodology. The mesh sensor package design is scalable so as to be compatible with standard flanged pipelines of size estimated to be <DN100 and >DN10. The new design solves the problems discussed related to prior state of the art while at the same time allowing the sensor to operate at higher temperatures and to be manufactured and assembled more easily and more cheaply. The pressure barrier is no longer guaranteed by an epoxy, as in prior state of the art developed by other researchers, but rather by a standard graphite gasket between the sensor housing flanges, the same type that would normally be sealing a bolted flange joint, and commercially available threaded sealing glands. While still maintaining space for the standard number of bolts for a given flange size, such sealing glands could conceivably allow for a very high number of electrode signals to be extracted. The ability to carry a large number of conductors through the pressure barrier, in addition to the housing flange design, enables the installation of multiple mesh sensors, three layer sensors, or other instrumentation such as thermocouples, enabling the reconstruction of additional flow properties from measured data such as velocity and interfacial area concentration.

A 16-transmitter, 16-receiver prototype sensor has been constructed for a DN80 pipeline; its individual components and some assemblies thereof have been tested in an autoclave at temperatures up to 285 °C in a liquid water-vapor environment with boiling at saturation pressure. Furthermore, a test section construction has enabled the sensor to temperature changes via the variable electrical conductivity of deionized water as a function of temperature to be investigated.

1. Introduction

Especially beneficial in the field of experimental nuclear reactor thermal-hydraulics are measurements at realistic fluid temperatures and pressures such as those found in commercial PWRs and BWRs. In this manner, the difficulties associated with scaling non-dimensional parameters from adiabatic experiments may be reduced or even avoided completely. New advanced instrumentation is needed to provide a larger density of data in time and space from thermal-hydraulic experiments at high temperatures and pressures than is traditionally achievable with thermocouples.

Mesh sensor technology has a storied history in both single-phase and two-phase flow studies in the context of nuclear reactor thermal-hydraulics since its inception in the late 1990's (Prasser et al., 1998; Peña and Rodriguez, 2015). Typically implemented are wire-mesh sensors (WMS) which use thin metallic wires as electrodes to measure the electrical conductance of a fluid in a regular grid of control volumes spanning typically the entire cross-section of a conduit at high frequencies of up to 10 kHz. The vast majority of mesh sensors have been designed for room tempera-

---

* Corresponding author.
E-mail addresses: kickhofel@lke.mavt.ethz.ch (J. Kickhofel), jiayang@student.ethz.ch (J. Yang), prasser@lke.mavt.ethz.ch (H.-M. Prasser).

http://dx.doi.org/10.1016/j.nucengdes.2017.07.020
0029-5493/© 2017 Published by Elsevier B.V.

Please cite this article in press as: Kickhofel, J., et al. Designing a high temperature high pressure mesh sensor. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.07.020

ture studies in adiabatic test facilities, often utilizing a salt tracer to observe mixing (Walker et al., 2009). Special techniques enable mesh sensors to measure capacitance or detect the given two-phase flow regime automatically (Silva and et al., 2010; Shaban and Tavoularis, 2014). By using two transmitting electrode layers or two neighboring sensors it is even possible to measure flow or bubble velocity by means of cross-correlation techniques (Prasser, 2013).

For ambient temperature, small diameter applications electrodes may be tensioned and fixed, typically by a soft solder, without experiencing plastic deformation. When wire-mesh sensors are built for larger-diameter conduits they have historically incorporated small tension springs, typically attached to one or both ends of each electrode wire to allow for higher wire tensions, keeping the electrode taut in the cross section. Examples of these sensors include the works of Betschart et. al. in which a wire-mesh sensor is installed in a square duct of 500 × 500 mm (Betschart et al., 2014).

This paper focuses on mesh sensor technology for high temperature and pressure flows. Prior state of the art in this domain is detailed primarily in publications by Prasser et. al. (2008), Dudlik et. al. (2008), Pietruske et. al. (2007) as well as in patents and reports originating from the Forschungszentrum Rossendorf (FZR, now HZDR) in Germany (Prasser et al., 2008; Pietruske and Prasser, 2007; Dudlik et al., 2008; Prasser et al., 2003, 1998, 2000). These publications demonstrate two distinct mesh sensor designs, rated for temperatures above 200 °C at saturation pressure (up to 286 °C and 6.5 MPa), both relying on high-temperature epoxies, rated to 180 °C and sometimes requiring active cooling, to ensure an effective pressure barrier. One design utilizes stainless steel wire electrodes attached to individual compensation springs to account for thermal expansion of the wire, the other uses large, lentil-shaped electrodes which are not fully secured such that they are allowed to thermally expand axially.

Proof-of-concept experiments with a prototype high temperature high pressure mesh sensor developed at the ETH Zurich have been performed by Kickhofel et al. (2015) in collaboration with the University of Stuttgart (Kickhofel et al., 2015). This paper will detail both the non-fixed electrode sensor which was utilized in those experiments at 280 °C and 7.5 MPa pressure as well as an extended discussion of the sensor design in general including necessary changes to extend the sensor to applications in flows at temperatures as high as 350 °C (with polyimide insulated conductors) or higher (in lieu of conductor insulation) and pressures up to 22 MPa. Fig. 1 shows prior state of the art along with the sensor technology described in this paper in a pressure-temperature space.

The following section will describe the mesh sensor package construction comprised of the housing flanges, hoses, sealing glands and sensor sandwich. Section 3.3 describes the prototype sensor with a non-fixed electrode design including calibration methodology. A discussion of potential alternate materials for various components of the mesh sensor is provided in this section. Briefly, in Section 4, the feasibility of a fixed-electrode WMS design without compensation springs is discussed. In Section 5 an early prototype of a fixed-electrode WMS with compensation springs is described followed, in Section 6, by some concluding remarks.

2. Mesh sensor package construction

The mesh sensor design is characterized by a separation of the components securing the integrity of the pressure barrier from the components comprising the mesh sensor itself, including electrodes. The housing flanges and multi-element sealing glands which ensure a sealed conduit are in-effect separate from the mesh sensor construction. The installation of the sensor package in standard flanged pipelines, typical of high temperature high pressure facilities, is straightforward and has been demonstrated in practice (Kickhofel et al., 2015). The sensor itself is comprised of mostly off-the-shelf components with the exception of the ceramic sandwich, which includes space for 16 -transmitter and -receiver electrodes, and the housing flanges.

Two flanges allow for the installation the mesh sensor in a pipeline within standard tongue-and-groove flanges, in this case of size DN80 (with custom inner diameter 71.8 mm) and pressure-number PN100, see Fig. 2. A test section at the ETH Zurich was constructed for testing sensor package prototypes within the DN80 flanges. The housing flanges maintain the traditional sealing strategy in that all eight bolts used to seal the pipeline remain unhindered, however, the bolts are lengthened considerably and instead of a single gasket, three gaskets are necessary. Along the axis of the pipeline the gaskets are concentric and of approximately the same area but are not overlapping such that the force between the two housing flanges generates significant torsion. For this reason standard stainless steels such as AISI 304 or 316L would experience irreversible ductile deformation at the temperatures of interest. The high strength low carbon martensitic-austenitic stainless steel EN 1.4418 was determined to be a suitable steel for this application.

The primary housing flange, which has been machined with an inner diameter of 115 mm provides sufficient space for the single carriers to be connected to the electrodes and routed out of the flange via two transmission conduits. Connected to each borehole

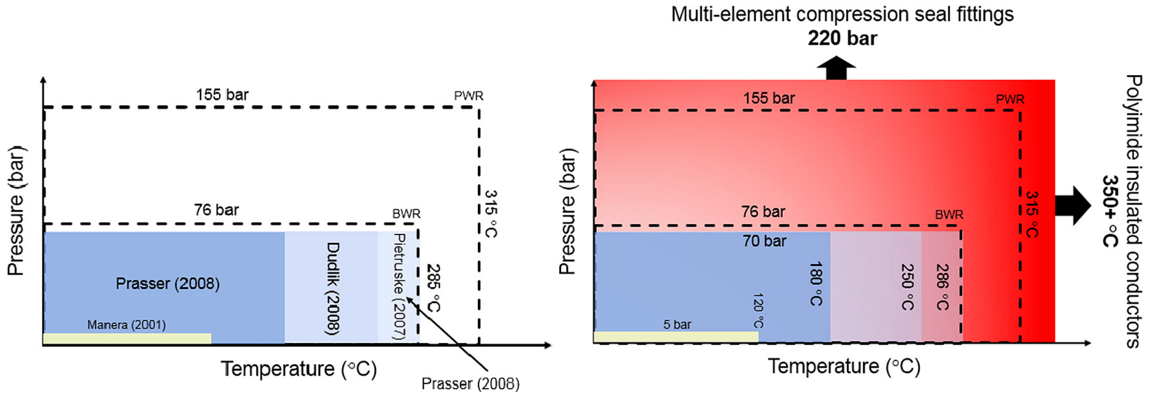

Fig. 1. Temperature and pressure capabilities of prior state-of-the-art and relevant publications (left) overlaid with the potential capabilities of the new mesh sensor package with T-p values (right, in red). Dotted lines indicate PWR and BWR reactor operating conditions in the T-p space (not to scale). (Prasser et al., 2008, 2003, 1998, 2000; Pietruske and Prasser, 2007; Dudlik et al., 2008; Manera et al., 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Please cite this article in press as: Kickhofel, J., et al. Designing a high temperature high pressure mesh sensor. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.07.020