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Numerical investigation of erosion of tube sheet and tubes of a shell and tube heat exchanger

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ABSTRACT

The failure of shell and tube heat exchangers caused by solid particle erosion has been a major problem in the oil and gas and other industries. Predicting erosion is still a developing art, an accurate simulation method is then significant to analyze the erosion characteristics in such complex geometry and determine erosion rate of metal surface. In this work a physical model was proposed to simulate the erosion of two-pass shell and tube heat exchangers with computational fluid dynamics. The simulation was performed for different feed fluid rates and a range of sand particle sizes from 0.1 to 1000 μm. The erosion rates of tube sheet, tube ends in the inlet plenum and the inner wall of tubes were monitored and the influences of flow pattern, particle size and particle behaviors on erosion were studied. The predictions are compared with the earlier studies and a good agreement was found. The particles can be classified into three groups based on the dependence of erosion rates of tube sheet and tubes on the particle size. The large particles (>200 μm) exhibited a near-linear influence on the erosion rates. The small particles (about 50–200 μm) produced approximate size-independence facet-average erosion rate of tubes, but the maximum local erosion rates of the tubes and tube sheet sharply increased with the decrease of particle size. The fine particles (<about 50 μm) resulted in low facet-average erosion rates but very high local erosion rate. The erosion at the tube sheet, tube end and tube surface also show different aspects of relation with particle size.

1. Introduction

Shell and tube heat exchangers are widely used for cooling and heat recovery in oil and gas production and other chemical processes. Erosion is one of major problems of the heat exchangers, when either fluid flowing through tubes or fluid passing through the shells contains solid particles, for instance, seawater is utilized for cooling, and runs at a velocity that likely causes the metal wear from the tube surfaces at its operating temperature (Kuźnicka, 2009; Lai and Bremhorst, 1979). The impingement of solid particles most often occurs on the inside surface of the tubes and near the tube entrances for shell and tube heat exchangers and also along the U bend for U-tube heat exchangers. Severe metal loss in some local areas of a heat exchanger not only requires frequent maintenance but also results in the failure of the heat exchanger, leading to very costly planned and unplanned maintenance, production loss and potentially environmental disasters.

Erosion process has been investigated extensively since decades with respect to the mechanism (Research and Markets, 2011) and the relationship between the amount of erosion and the variables dominating the erosion, including the materials of targets (Laguna-Camacho et al., 2013), fluid properties and velocity (Kesana et al., 2013a,b), properties and velocity of the solid particles (Kesana et al., 2013a,b), and temperature (Naz et al., 2015). Despite these fundamental studies and recent advances in computational fluid dynamics the erosion process has yet to be fully predicted with reasonable accuracy even for fairly dilute suspension of solid particles. Most prediction studies mainly concern the erosions on simple geometries, such as straight and sudden contraction tubes (Badr et al., 2005; Duwig et al., 2008; Habib et al., 2007, 2008), elbows (Chen et al., 2004; Mazumder et al., 2008; Njobuenwu and Fairweather, 2012; Safaei et al., 2014; H. Zhang et al., 2012), tees (Chen et al., 2004), U bends, orifices (Nemitallah et al., 2014), pipe and wall cavities (Lin et al., 2014; Wong and Solnordal, 2012; Wong et al., 2013a,b) and flat plates (Wong et al., 2012). Predicting the erosion process in shell and tube heat exchanger is more

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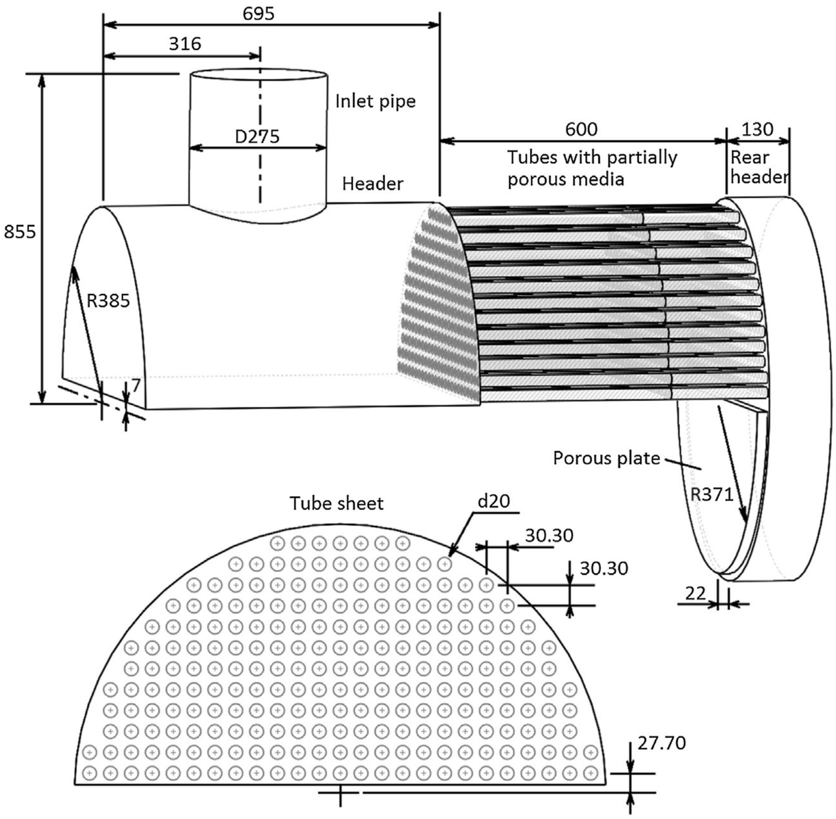

Fig. 1. The main dimensions of the model for a shell and tube heat exchanger and the tube sheet indicating the arrangement of tubes (dimensions are in mm).

challenging because of the complexity of flow field in the regions likely to be worn, i.e., the inlet head and the downstream regions from the tube entrances. A single fluid stream expands into a large area and then divides into multiple smaller streams; turbulence leads to a very high velocity in some local regions. The flow field much depends on the geometry of the heat exchanger and the properties and velocity of the fluid.

The tube entrance of shell and tube heat exchanger is the most critical region with respect to erosion failure. The rate of erosion greatly relates to the flow characteristics in this region. It has been found that a cross flow pattern near some tube inlets considerably contributed to the erosion of the tubes (Bremhorst and Lai, 1979). Low velocity caused accumulation of deposits, reduction of tube diameter and sometimes complete blockage of tubes (Ranjbar, 2010). The effects of flow velocity and sand particle size on the rate of erosion in a shell and tube heat exchanger were investigated numerically (Habib et al., 2006, 2005), where k-ε turbulence model was used for fluid and the Lagrangian approach was employed for tracking particles. The influence of particle motion on the fluid flow field was neglected. Half of the heat exchanger having 38 tubes were considered based on the assumption of symmetrical flow. However, both experimental and numerical studies of a sudden symmetric expansion flow (Bremhorst and Lai, 1979; Duwig et al., 2008; Sugawara et al., 2005; Ternik, 2009; Velasco et al., 2008) have shown that the flow field is asymmetry, which is attributed to the competing effects of shear thinning and inertia on the size of the corner vortex (Mishra and Jayaraman, 2002). The asymmetric flow in the head of shell and tube heat exchanger is similar in nature to asymmetries noticed in plane expansion flow. A full geometry was used in the modelling of flow field in the symmetrical head of a shell and tube heat exchanger (Bremhorst and Brennan, 2011). In the modelling, the Reynolds-Averaged Navier–Stokes (RANS) equations for continuity and momentum equations and the SST-k-ω turbulence model were used. The prediction of erosion/corrosion of the tube inlets was based on the characteristics of flow field as solid particles were not included in the modelling. Accurate prediction of erosion rate depends on the determination of the particle impact velocity, impingement angle and the frequency of impacts on concerned surfaces. These particle variables can be derived from their trajectories. The Lagrangian approach has been demonstrated in modelling particle motion in various geometries for dilute systems (Badr et al., 2006; Parsi et al., 2014; Wong et al., 2013a,b).

Although erosion of tube sheet, tubes and tube ends is a common problem that influences the performance of shell and tube heat exchangers, there is no research published in the literature that deals with the effect of various parameters on the erosion of these targets. The present work aims to study the erosion at the entrance region and tubes of the heat exchanger and the effect of particle behaviors and fluid flow on the rate of erosion. A physical model is proposed based on initial computational fluid dynamics simulation of fluid flow in a shell and tube heat exchanger, which provides the flow characteristics in the heat exchanger and the dependence of results on the momentum and turbulence models adopted. The simulation is performed for different feed fluid rates and particle sizes in a range of 0.1–1000 μm.

2. Model description

2.1. Physical model

The simulations were performed for the inlet head inside and the flow development regions in tubes close to the tube sheet of a typical shell and tube heat exchanger with two-pass construction. Fig. 1 shows the geometry of the physical model. Fluid enters from the side entry into the head and then is distributed into 230 tubes at the tube sheet. The liquid through each tube first experiences a