Applied Thermal Engineering 110 (2017) 710–719

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Theoretical and experimental study of a synchronal rotary multiphase pump at very high inlet gas volume fractions

Xu Yang *, Congcong Hu, Yao Hu, Zongchang Qu

School of Energy and Power Engineering, Xi'an Jiaotong University, 28 Xianning West Road, Xi'an 710049, China

HIGHLIGHTS

- A new model of the synchronal rotary multiphase pump is developed.
- The experiment is implemented under the inlet gas volume fractions of 0.91–0.98.
- The inlet gas volume fraction has a significant effect on the pump behaviour.
- The pump exhibits lower pump efficiency at the higher inlet gas volume fractions.

ARTICLE INFO

Article history:
Received 28 March 2016
Accepted 29 August 2016
Available online 31 August 2016

Keywords:
Positive-displacement pump
Gas volume fraction
Two-phase flow
Thermodynamic process
Leakage
Heat transfer

ABSTRACT

Theoretical and experimental analyses are performed to investigate the pumping behaviour of a synchronal rotary multiphase pump (SRMP) at very high inlet gas volume fractions (GVFs). A comprehensive SRMP model is developed to predict the pump performance at very high inlet GVFs, including the steady-state behaviours and the transient distributions of interesting variables during pump operation. The experimental work is implemented using N32 oil and air as the working fluids to measure the global performance parameters of the SRMP at the inlet GVFs of 91–98% and different differential pressures. The SRMP model is validated by comparison of the simulated and experimental results. The results show that the inlet GVF has a significant effect on the pump behaviour. At a given differential pressure, the leakage loss increases dramatically with the inlet GVF, which results in a significant decrease in the volumetric flow rate of the SRMP. Because of the large proportion of shaft power wasted by the high-pressure back flow, the SRMP exhibits lower pump efficiency at the higher inlet GVFs.

1. Introduction

Multiphase pumping is one of the most promising technologies in the petroleum industry, which essentially consists in adding hydraulic energy to unprocessed gas-liquid mixtures and transporting them through one pipeline. This technology makes longer tie-back distances possible for the production steam before separation in the processing facility, which is of special interest in deep water and onshore use, and in remote or hostile environments [1,2]. As using multiphase pumps to boost gas-liquid mixtures, multiphase pumping technology allows production to increase through the reduction of well-head pressure and the complete recovery of associated gases [3,4]. It also allows significant cost savings through the simplification of conventional production facilities [5].

In recent years, because of the benefits of multiphase technology, the demand placed on the multiphase pump unit, which is the key device in the multiphase pumping system, has steadily increased. So far, several types of multiphase pump have been developed, which are categorised mainly as positive-displacement pumps and rotodynamic pumps [6]. Compared to the rotodynamic multiphase pump, the positive-displacement multiphase pump exhibits more reliable performance in gas-liquid boosting, especially in applications with high pressure and high gas volume fraction (GVF). Based on its use in field applications around the world, the twin-screw multiphase pump is the most successful positive-displacement pump in operation [7–9]. It has the proven ability to handle gas-liquid mixtures with any inlet GVF from 0 to nearly 100% [10,11]. However, this pump is sensitive to the solid particles contained in the working fluids, and its manufacturing cost is also quite high because its rotors are formed by complex profiles [12].

The synchronal rotary multiphase pump (SRMP) is a new type of positive-displacement multiphase pump that is structurally

* Corresponding author.
E-mail address: yangzx@mail.xjtu.edu.cn (X. Yang).

http://dx.doi.org/10.1016/j.applthermaleng.2016.08.204
1359-4311/

Nomenclature

A	area of surrounding wall [m^2]
C	coefficient of Lockhart-Martinelli's correlation [–]
C_A	coefficient of Armand-type correlation [–]
c_p	specific heat capacity of gas-liquid mixture [J/(kg k)]
D_h	hydraulic diameter [m]
f	friction factor [–]
G	mass velocity [kg/(m^2 s)]
h	specific enthalpy [J/kg]
k	convective heat transfer coefficient [J/(m^2 K)]
La	non-dimensional Laplace constant [–]
m	mass [kg]
n	shaft speed [rev/min]
P_e	effective power consumption [W]
P_i	indicated power consumption [W]
P_{sh}	shaft power consumption [W]
Pr	Prandtl number [–]
p	pressure [Pa]
Q	heat energy [J]
q_{th}	theoretical volumetric flow rate [m^3/h]
q_m	mass flow rate [kg/s]
R_{cy}	cylinder radius [m]
Re	Reynolds number [–]
R_h	curvature radius [m]
R_g	gas constant [J/(kg K)]
R_{ro}	rotor radius [m]
S	slip ratio [–]
T	temperature [K]
U	internal energy [J]
u	velocity [m/s]
u	characteristic velocity [m/s]
V	control volume [m^3]
X	Lockhart-Martinelli parameter [–]
x	gas mass fraction [–]
z	length of leakage gap [m]

Greek symbols

α	gas void fraction [–]
β	gas volume fraction [–]
γ	height of leakage gap [m]
ε	surface roughness [m]
η	Pump efficiency [%]
λ	conductive heat transfer coefficient [J/(m K)]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
φ	shaft angle [rad]
φ^2	two-phase friction multiplier [–]
ω	angle velocity of rotor [rad/s]

Subscripts

G	gas-phase
in	inflow
L	liquid-phase
out	outflow

simple and easy to manufacture. The SRMP design is based on the concept of the synchronal rotary mechanism that has been used in gas compressor [13–15]. The similar structure called revolving vane mechanism also has been used in the gas compressor and expander for refrigeration system [16,17]. This type of mechanism has a unique structure in which the rotor is allowed to rotate together with the cylinder. In addition to its superior mechanical efficiency, the SRMP has the ability to handle gas-liquid mixtures with any inlet GVF due to its rotating suction and discharge ports [18]. Furthermore, due to the relative motions of the cylinder and rotor, solid particles contained in the working fluids are also easily squeezed out along the flow path of the working fluids.

Because the SRMP is a new type of multiphase pump, several studies have already been published. In the literature [19], the structural design and dynamic characteristics of the SRMP were theoretically investigated. The subsequent study focussed on the mechanical loss the SRMP and the preliminary experiment using liquid as working fluids [18]. In the literature [20], the pump behaviour of the SRMP with inlet GVFs of 0–90% were theoretically and experimentally investigated. A theoretical model of the SRMP was developed in which the thermodynamic process was treated as an adiabatic process, and all of the chamber flows were assumed to be homogeneous gas-liquid flows. Such a SRMP model satisfactorily predicts the pump behaviour when the inlet GVF is no more than 90%. However, when the inlet GVF rises above 90%, the predication errors of the SRMP model increase significantly due to the change in the two-phase flow characteristics and the increase in the compression heat of the gas phase. Because the SRMP can handle two-phase fluids with a very high inlet GVF, it is quite important to develop a new SRMP model and implement further investigations of the pump behaviour under extreme operating conditions such as very high inlet GVFs up to almost 100%.

In this study, further investigations are carried out that focus on SRMP behaviour when the inlet GVF is more than 90%. A new SRMP model is developed to calculate all interesting flow variables and thermodynamic parameters during pump operation. The following experimental works are intended to verify the new model and analyse the thermodynamic process of the SRMP. Finally, the results of the simulations and experiments are discussed.

2. Theoretical model of the SRMP

Under the condition of very high inlet GVFs, the working process of the SRMP is more like that of the positive-displacement compressor. Similar to the theoretical models of positive-displacement compressors [21–24], the comprehensive model of the SRMP generally includes the geometrical characteristics, thermodynamic process, leakage flow, heat transfer and mechanical loss. Such a simulation model can be used to calculate the transient pressure and temperature in the working chambers and the steady flow rate and pump power consumption. In this section, the theoretical model of the SRMP for extreme conditions with very high inlet GVFs is developed. Compared to the model for conditions with lower inlet GVFs [20], the present model is developed in more detail to take into account the heat transfer between the working fluids and chamber walls, and it also includes a new leakage model using the separated two-phase flow model. Because the geometrical model and mechanical loss model of the SRMP are the same as those for conditions with lower inlet GVFs, the following formulae mainly concentrate on the thermodynamic process, leakage flow and heat transfer.

2.1. Modelling of thermodynamic process

As shown in Fig. 1, the SRMP basically consists of a rotor, a sliding vane and a cylinder with two end covers. The rotor and cylinder are eccentrically arranged such that the working chamber is