

Numerical simulation of Venturi ejector reactor in yellow phosphorus purification system



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HIGHLIGHTS

- Venturi ejector reactor is used in yellow phosphorus purification system to obtain high purity phosphorus.
- We study the changes of vacuum region and the performances of Venturi ejector reactor with different operating pressure.
- The whole study is aim to investigate the operating conditions, rather than to find out the small details of the chemical reaction.

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ABSTRACT

A novel type of Venturi ejector reactor, which was used in a pilot plant test in a factory in Guizhou in China, was developed to overcome the insufficiency of chemical reaction in the stirred-tank reactor in yellow phosphorus purification system. The effects of different working medium, the changes of vacuum region, and the performances of the Venturi ejector reactor with different operating pressure were investigated by FLUENT. Results show that the absolute value of vacuum pressure of single-phase flow was smaller than two-phase flow at the same operating conditions, which meat two-phase flow has a higher suction capability. Reflow phenomena occurred near the exit of suction pipe and nozzle. The former reflow which leads to energy loss of vacuum region was undesirable, and the latter was beneficial to the dispersion of liquid yellow phosphorus. With a flow rate ratio below 0.45, the performance of the Venturi ejector reactor was effective. By adjusting the operating pressure, a proper flow rate ratio could be satisfied to meet the production needs in yellow phosphorus purification system.

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1. Introduction

Venturi ejector reactor (VER) is one type of fluid machine based on injection technology and jet turbulent diffusion effect (Lu, 2004). Due to its favorable features in mass transfer and mixing, VER has been widely used in many processes such as nuclear power plant engineering, chemistry, petroleum, metallurgy, refrigeration and food industry to obtain a vacuum environment for various special techniques.

Yellow phosphorus purification system (YPPS) is aimed to obtain high purity phosphorus which is the basic raw material of many phosphorus compounds and derivatives to meet industrial needs. Generally, the purification processes between liquid yellow phosphorus and oxidizing medium happen in the stirred-tank reactor (Liu et al., 2010). However, the chemical reaction is not sufficient for the reason of low dispersion of yellow phosphorus after the

equipment was amplified. To solve this problem, VER used as both disperser and reactor in safe and reliable conditions was developed and manufactured to apply to YPPS.

Most researches focused on the aspects such as the optimization of the size (Long et al., 2008a,b), the experimental study (Chunnanond and Aphornratana, 2004; Dumaza et al., 2005; Shah et al., 2011; Eames et al., 2012), CFD simulation (Utomo et al., 2008; Levy et al., 2002) or the spontaneously condensing phenomena research (Wang et al., 2012). Despite the extensive research of VER, there are few studies of the application of VER in YPPS. Consequently, this research is necessary and of great significance.

Generally, there were three main methods that were applied in the research – the theoretical calculations, experimental research and numerical simulation. Because of the low ignition point, yellow phosphorus is dangerous and cannot be exposed to the air to prevent from spontaneous combustion. Traditional experiment-based research required good safety measures and a lot of material resources. On the contrary, numerical simulation, because of its high efficiency and low cost, could adapt to a variety of variables, and has been widely used in engineering practice. In this research,

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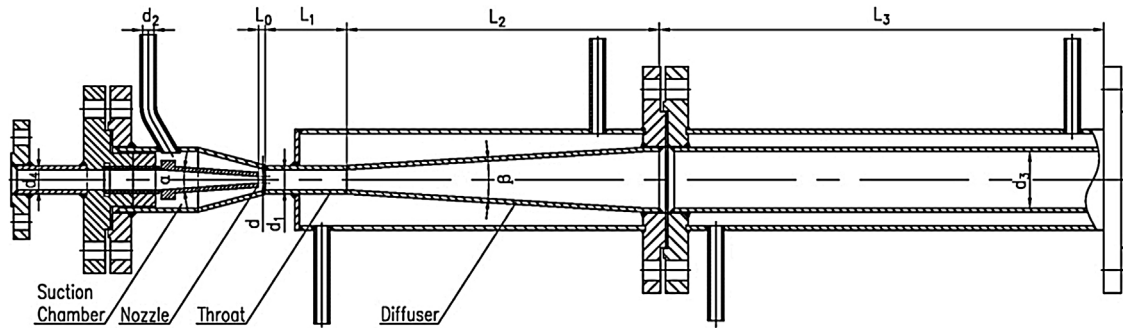


Fig. 1. Structure of Venturi ejector.

a commercial CFD code FLUENT 6.3 was selected as a platform for CFD simulation.

The present study focuses on the effects of different working medium, the changes of vacuum region, and the performances of VER with different operating pressure. The validity of the numerical simulation results are also verified from the experimental data which came from the pilot plant test in a factory in Guizhou. The process of chemical reaction are treated as a black box, and we do not care the detailed chemical process, but investigate the inlet and outlet result before and after the chemical reaction, then find out the best operating conditions to meet the needs of industrialization.

2. Principles and basic structure of VER

VER is a device without moving parts, in which the primary fluid is used as an energy source to pump the secondary fluid from a pressure much lower than the primary fluid's to a higher pressure. All thermodynamics processes in VER rely on the direct transport phenomena between the primary and secondary fluids.

The principle of VER is to utilize the kinetic energy of a high velocity liquid jet to pump the secondary fluid and to create a fine mixing of the two phases. The primary fluid is pumped into the system at a high velocity through a nozzle. According to Bernoulli's principle, a vacuum region is created in the suction chamber, into which the secondary fluid got pumped. The pressure decreased in the region of nozzle exit. After that, the primary and secondary fluids mix in the throat. The pressure is recovered in the diffuser at the exit of the mixing chamber.

A two dimensional sketch of VER is shown in Fig. 1. It can be divided into the five parts: suction chamber, nozzle, throat (mixing chamber), diffuser and draft tube. The pipe around the diffuser and draft tube that prevents yellow phosphorus caking gives heat preservation.

In YPPS, the effects of purification are favorable when the ratio of primary fluid and secondary fluid maintains from 5:1 to 10:1. To meet this need, the geometric parameters of VER combined with empirical formula (Lu, 2004) are summarized in Table 1.

Table 1
Geometric parameters of VER.

Geometric parameters	Value (mm)
Inlet diameter of nozzle, d_4	18
Outlet diameter of nozzle, d	6
Diameter of suction pipe, d_2	10
Diameter of throat, d_1	18
Diameter of draft tube, d_3	50
Nozzle-to-throat clearance, L_0	6
Length of the throat, L_1	72
Inlet angle of throat, α	30°
Divergence angle, β	7°
Length of the throat, L_2	280

The performance of VER is measured and evaluated by the performance parameters of the following dimensionless forms:

$$\text{Flow rate ratio : } q = \frac{Q_s}{Q_0} \quad (1)$$

$$\text{Pressure ratio : } h = \frac{\Delta p_c}{\Delta p_0} = \frac{p_3 - p_2}{p_1 - p_2} \quad (2)$$

$$\text{Area ratio : } m = \frac{A_{th}}{A} \quad (3)$$

where Q_s is the flow rate of the suction inlet flow; Q_0 is the flow rate of the working flow; p_1 is the primary fluid pressure; p_2 is the secondary fluid pressure; p_3 is the discharge pressure; A_{th} is the sectional area of the throat; A is the sectional area of the nozzle exit.

3. Numerical simulation

3.1. Geometries and grids

The geometric parameters of VER are summarized in Table 1.

Since the internal flow field of VER belonged within the limited space of the irregular area (converging section and diverging section), the entire calculation regions should not be arranged in a single uniform grid, but in an irregular grid with changeable size and density according to the velocity gradient, in order to assure that different parts of the node spacing were relatively stable. The generated analysis meshes showed in Fig. 2.

The meshes were made of approximately 220,000 nodes of 3D-tetrahedral/hexahedron hybrid mesh using Gambit 2.3.16.

3.2. Case setup

Since the primary and secondary fluids used in this study were different liquids, the assumption of incompressible flow was appropriate. As for the circular jet flow, the realizable k- ϵ model has an outstanding performance (Wang, 2004) and was selected to govern the turbulence characteristics. The pressure-based solver and the first order upwind scheme were selected as the discretization scheme of the convection terms and the diffusion terms of the governing equations.

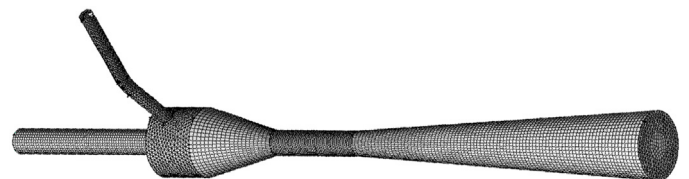


Fig. 2. Grid and computational domain.

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