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Maximization of energy recovery inside supersonic separator in the presence of condensation and normal shock wave

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ABSTRACT

Natural gases provide around a quarter of energy consumptions around the globe. Supersonic separators (3S) play multifaceted role in natural gas industry processing, especially for water and hydrocarbon dew point corrections. These states of the art devices have minimum energy requirement and favorable process economy compared to conventional facilities. Their relatively large pressure drops may limit their application in some situations. To maximize the energy recovery of the dew point correction facility, the pressure loss across the 3S unit should be minimized. The optimal structure of 3s unit (including shock wave location and diffuser angle) is selected using simultaneous combination of normal shock occurrence and condensation in the presence of nucleation and growth processes. The condense-free gas enters the non-isentropic normal shock wave. The simulation results indicate that the normal shock location, pressure recovery coefficient and onset position strongly vary up to a certain diffuser angle ($\beta = 8^{\circ}$) with the maximum pressure recovery of 0.88 which leads to minimum potential energy loss. Computational fluid dynamic simulations show that separation of boundary layer does not happen for the computed optimal value of β and it is essentially constant when the inlet gas temperatures and pressures vary over a relatively broad range.

1. Introduction

Fossil fuels provide more than 80% of all primary energy supply capacity of the entire world [1]. Natural gases have several important applications such as using them as raw materials in various chemical industries, as fuel in combustion engines and to generate electricity or heat [2]. For these reasons, the consumption of low-calorie natural gases are increased globally [3]. Both water and hydrocarbon dew point corrections are essential for safe transmission via pipelines and from economic viewpoints. Various processes such as absorption, adsorption, cryogenic and membranes are traditionally used to adjust water dew point [4]. Supersonic separators (3S) can provide same separation efficiency with better economy using more compact facilities, no chemical consumption, better environmental impacts, more selective separations and higher reliability compared to the above processes. Despite of all these advantages, the major shortcoming of the 3S unit is its relatively large pressure loss due to normal shock occurrence after the collection point inside the diffuser.

Fig. 1 illustrates a typical processes flow diagram (PFD) to separate water vapor and excess heavy hydrocarbons from sweet natural gases using a 3S unit. As can be seen, after separation of relatively large droplets of liquid water and hydrocarbon (d > 40 μm) in the 3-phase separator, the feed gas enters the plenum chamber of a 3S unit where a swirling motion will be induced in the gas stream to provide extremely large radial acceleration especially in diverging sections of the Laval nozzle. Evidently, the gas Mach number reaches unity at the throat location and then become greater than 1 inside the diffuser.

Consequently, both gas pressure and its temperature are dramatically reduced due to the transformation of potential energy into kinetic energy. The extremely cold conditions inside the Laval nozzle lead to condensations of almost all of the water vapor and a great part of heavier hydrocarbons from lighter gases such as methane and ethane. The separated water and hydrocarbon droplets create two distinct liquid films over the diffuser walls due to the swirling motion of the gas. Clearly, the heavier water film lies below the lighter condensed liquid hydrocarbon.

After both water and hydrocarbon dew pints reaches to their required values, the liquid streams are then separated from the gas

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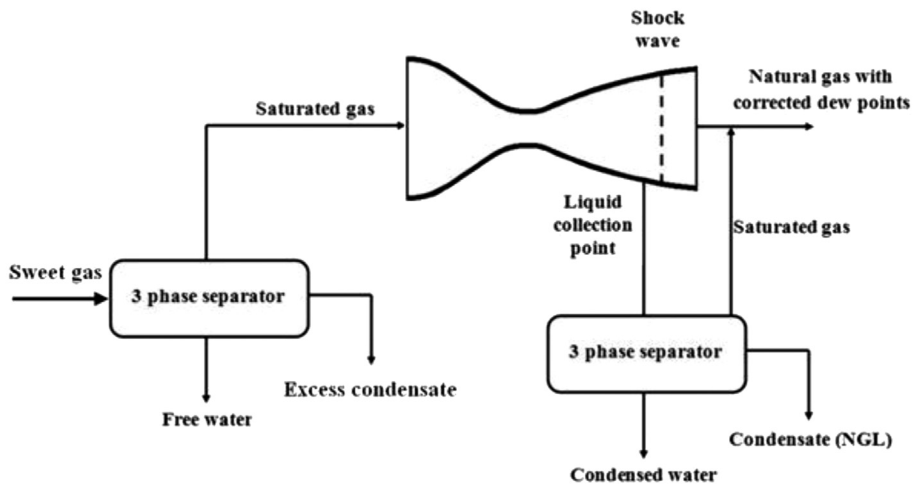

Fig. 1. Typical PFD for natural gas dew point correction via supersonic separator.

using appropriate withdrawal section at the collection point. Afterwards, the natural gas pressure and temperature are recovered before the gas leaving 3S unit and entering the transmission pipeline. Normal shock phenomenon is usually used after collection point to increase both temperature and pressure of the natural gas. Due to the non-isentropic behavior of the shock wave, exceedingly large pressure difference exists between the 3S inlet and outlet gas streams, which is the main drawback of the 3S unit. The liquid hydrocarbon and water stream leaving the Laval nozzle is then flashed at relatively higher temperature to return some of the swallowed light natural gas back to the main stream.

The following section briefly reviews more recent articles focusing on the normal shock performance inside various supersonic separators.

Jassim et al. studied the performance of high-pressure natural gas in the supersonic nozzles via computational fluid dynamic for single phase flow. The first part [5] investigated natural gas behavior under real and ideal situations via analyzing the influences of natural gas properties and location of shock wave. The second part [6] dealt with the effects of nozzle geometry and vorticity on the shock wave position. Malyshkina [7] investigated the shock wave structure and the analysis of gas dynamic in the supersonic separator using numerical model assuming inviscid flow of the natural gas.

Karimi and Abdi [4] investigated the influences of the inlet pressure, temperature and back pressure on the shock positions in the supersonic nozzle, using a combination of MATLAB and HYSYS packages. Wen et al. [8] predicted the position of shock wave location in the presence of swirling for single phase flow of natural gas inside a customized supersonic separator by incorporating a central body and equipped with a swirling device composed of special vanes. In another study [9] the same team investigated three different diffuser structures for the pressure recovery of a single phase natural gas flow inside Laval nozzle. The simulation results indicated that the conical diffuser which had the highest pressure recovery was more adequate.

Mahmoodzadeh Vaziri and Shahsavand [10] used a generalized radial basis function (GRBF) artificial neural networks to investigate the effect of various parameters (e.g., inlet pressure, feed temperature, inlet velocity, pressure recovery efficiency via shock wave and exit gas velocity) on the geometry and dimensions of 3S unit for a single phase flow.

Yang et al. [11] studied the theoretical and numerical aspects of the pressure recovery inside the supersonic separators for natural gas dehydration, without considering the water condensation phenomenon. They reported that their numerical simulation results are always smaller than the so called “ideal data” with the maximum error of about 8.69%. Furthermore they investigated the effects of three expansion ratio (defined as exit to throat areas of 1.118, 1.513 and 2.131) on the gas dynamic parameters for a fixed shock location. They concluded that the increase in the expansion ratio can generate a larger gas Mach number at the shock location, leading to lower corresponding pressure and temperature which can produce more liquid water. As it was mentioned, no real condensation process is considered in their work. Furthermore, in actual situation, the normal shock location is a function of the entire condensation process and can't be considered fixed as they assumed for a single phase flow. These issues will receive more attention in the coming sections of this work.

Cao and Yang [12] investigated the effect of various pressure recovery scenarios on the natural gas dehydration performance of an experimental supersonic separator with an ellipsoidal central body. They concluded that both inlet pressure and temperature have negligible effect on the dehydration performance, especially when the mass flow rate meets the separator working requirement. Bian et al. [13] studied the structural improvements of certain 3S units via numerical simulation in the absence of nucleation and growth processes and condensation phenomenon. They concluded that the improved 3S structure with 47.5% pressure loss had a good cooling condition when the inlet pressure was 600 kPa. Haghighi et al. [14] recently reviewed most of the comprehensive studies performed on the 3S units.

In our 2013 work [15], the capabilities of various 3S units were investigated for separation of water vapor and hydrogen sulfide from natural gas stream in the absence of pressure recovery and normal shock wave. The simulation results indicated that the 3S units are suitable for reducing the natural gas impurities to their permissible values. In our 2014 article [16] it was clearly shown that selective dehydration and hydrocarbons dew point corrections of natural gas can be successfully achieved in a 3S unit for multi-component and multi-phase flow.

As mentioned earlier, the major drawback of a 3S unit is the pressure loss along the nozzle which is the main object of the present work. Large pressure drops across a 3S unit limits its application as dew point correction facility. For example, the sweetened gas leaving the gas treating unit has a pressure of around 7 MPa and it should be injected to the main transmission line at the highest possible pressure. Therefore, successful pressure