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Supersonic gas separators: Review of latest developments

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ABSTRACT

Supersonic separator is a new technology with applications in gas dehydration and hydrocarbon dew pointing. Many research studies have investigated the design, performance and efficiency, economic viability, and industrial applications of these separators. Experimental facilities, pilot plants, and full scale industrial platform applications along with theoretical, analytical, and numerical modelling are some of the tools used in these studies. This review has found that while several aspects of this study are well studied, considerable gaps within the published literature still exists in the areas such as study of supersonic flows containing microscopic liquid droplets and liquid wall film.

1. Introduction

Supersonic separators combine the cooling properties of a converging–diverging nozzle with the principles of centrifugal separation. The concept was developed over half a century ago and has been modified over the subsequent decades. Garret (Garret et al., 1968) proposed a device for separation of condensable (heavy) components from a gas mixture where the outlet diffuser of a converging–diverging nozzle is attached to a curved channel. The expansion of the gaseous mixture creates a cooling effect and subsequent condensation of heavy components of the mixture and the curved channel separates the liquid droplets due to the high (supersonic) velocities and centrifugal force. Garret used a rectangular cross section for the initial design of his device and a permeable wall for the outer part of the curve to collect the liquid droplets. In these experiments, temperatures were calculated to depress about 100 °F while maintaining a flow Mach number of 2.2 in a natural gas mixture expansion from 12.4 MPa (1800 psi) to 1.14 MPa (165 psi). He did however report hydrate plugging the permeable wall, requiring the use of inhibitors. A number of patents (Garret, 1970; Garret and McDonald, 1970a; Garret and McDonald, 1970b and Garret, 1971) resulted from this design. A patent for a separator designed to remove particulate matter from a carrier gas uses a similar approach (Linhardt and Beveridge, 1981). In this design, a converging nozzle accelerates the carrier gas to Mach 1.0. The flow is then subjected to a combination of curved channel and deflecting surfaces to separate the flow of the particulate matter from clean gas. In related work by Nasikas, droplets are separated by subjecting the two phase supersonic flow to a normal shockwave (Nasikas, 1994). The gas phase will slow down across the shockwave, whereas the droplets will continue to travel at significantly higher velocities comparable to pre-shock supersonic flow. The flow then goes through a slight curve to collect droplets near the outer wall, and a separator plate removes the droplets stream. This separator design has also been proposed as part of a drying heat pump system (Nassikas, 1991).

Based on an extensive literature review, there appears to be little follow-up work on these designs including modelling or experimental data. The basis for the development of modern supersonic separators for the processing of natural gas was however re-established by the mid-nineties. The pioneers of this technology are two separate groups that developed their designs relatively parallel to each other, namely Twister BV and Translang Technologies. Several other researchers have studied these separators since then. The following is a summary of the reviewed literature in a tabular format. Table 1 is a summary of the reviewed literature that contains some form of experimental work. Table 2 represents all publications that contain numerical modelling of the supersonic separators. Note that a few of the reviewed literature that have

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Table 1
Summary of publications with reported experimental results.

Geometry	Publication	Measurement tools	Reported values	Working fluid
Nozzle with curved diffuser	(Garret et al., 1968)	Pressure Temperature Flow rate	Pressure, Flow rate through permeable wall	Natural gas mixture
	(Haghighi, 2010; Haghighi et al., 2013)	Pressure Temperature Flow rate	Pressure, Flow rate	Air
Circular nozzle (hollow tube)	(Liu et al., 2005a; Liu et al., 2005b)	Pressure Temperature Flow rate Humidity	Dew point (reduction), Temperature	Wet air
	(Liu et al., 2014)	Pressure Temperature Flow rate	Separation efficiency	Air and water droplets
	(Schinkelshoek and Epsom, 2006a)	Reports of 5 test facilities		
	(Feygin et al., 2006; Alfyorov et al., 2005; Brouwer et al., 2004)	Reports of 4 test facilities		
Annular Nozzle	(Wen et al., 2012a; Wen et al., 2011a)	Pressure Temperature Flow rate Humidity	Separation efficiency, Mass flow rate	Wet air
	(Ma et al., 2009)	Pressure Temperature Flow rate Composition	Water and ethanol removal	Air and ethanol mixture
	(Samawe et al., 2014)	Pressure Temperature Flow rate Composition	Pressure	Methane and CO_2 mixture

reported numerical work are omitted from this table since no particular information regarding the modelling was included within the text. Finally, Table 3 presents the cited works that have developed mathematical relations based on theoretical and analytical fundamentals in order to predict certain aspects of the supersonic separators and their performances. A detailed review of the literature is presented in the chapters that follow.

2. Twister BV

Prast, who later became associated with Twister BV, investigated the nucleation and growth of droplets in a 2D supersonic Laval nozzle (Prast et al., 1996). Numerical modelling was compared with experimental density field visualizations for validation purposes. The results showed an increase in temperature and pressure due to release of latent heat following the nucleation of droplets in the supersonic diffuser of the nozzle. A sensitivity analysis on the size of the nozzle was performed by repeating the simulation for 2× and 4× scaled nozzles. It was determined that by increasing the size, nucleation rate reduced and growth rate increased. By superimposing droplet radius and nucleation rate along the nozzle it appears the droplet radius has a non-zero value for approximately one third of the length of the diffuser that falls behind the location where first nucleation occurs; which cannot be valid. A possible explanation is the existence of another nucleation zone at the throat position which is not shown or discussed within the paper.

Twister separators are based on air drying devices originally developed in 1989 by Stork Product Engineering BV (Schinkelshoek and Epsom, 2006a). Twister BV is a company launched in year 2000 as a joint venture between Shell and the Beacon Group for the development of the first generation of supersonic separators, trademarked *Twister* (Okimoto et al., 2000). This model used a deflecting blade in the supersonic section of the nozzle to generate the swirl required for separation of condensed particles and is now referred to as Twister Mark I (Fig. 1). Initial comparisons with Joule–Thompson valve, turboexpanders, and mechanical refrigeration separation systems indicated savings in power requirements, equipment size and weight, and total costs associated with Twister systems where only caveats are associated with flow rate flexibility and narrow turn down ratio. By 2002, Twister had operating experience in five different gas plants, commercial contracts were already in place for field operations, and research into subsea units was launched in collaboration with FMC Kongsberg Subsea (Okimoto and Brouwer, 2002). Some of the offshore and subsea applications including natural gas dehydration and dew-pointing and the first commercial application of Twister dehydration system on Shell's B11 platform offshore Malaysia have been discussed in limited detail (Brouwer and Epsom, 2003) (Brouwer et al., 2004) (Okimoto and Brouwer, 2003). In an effort to improve the performance of Twister separators, Twister BV developed subroutines for the commercial CFD package CFX (of ANSYS) to account for high pressure compressible flow, multi-component gas mixture, and non-equilibrium condensation using population balance models (Jones et al., 2003). The design of the nozzle was optimized by incorporating a central body and an annular nozzle configuration (Prast et al., 2005). The swirl generation was also moved upstream, in the subsonic part of the nozzle inlet (Twister Mark II – see Fig. 2) (Schinkelshoek and Epsom, 2006b). The nozzle geometry was designed using a parametric study to optimize cooling rate, mass flow rate, minimum inner body radius, expansion ratio, and liquid load to improve efficiency in terms of pressure loss across the device and liquid recovery. A friction term was included to account for the losses associated with the liquid film on the walls. Model geometry was optimized in a quasi 1-D simulation set-up, and then used in 3-D pie section models to study the performance of the separator. These models were validated by experimental data. The models showed good agreement with the data with respect to pressure and a maximum error of about 30% with respect to liquid recovery. A new multiphase flow loop test facility in Netherlands