

# Experimental Study on Dehumidification Performance of Supersonic Nozzle

Esam Jassim

**Abstract**—Supersonic nozzles are commonly used to purify natural gas in gas processing technology. As an innovated technology, it is employed to overcome the deficit of the traditional method, related to gas dynamics, thermodynamics and fluid dynamics theory. An indoor test rig is built to study the dehumidification process of moisture fluid. Humid air was chosen for the study. The working fluid was circulating in an open loop, which had provision for filtering, metering, and humidifying. A stainless steel supersonic separator is constructed together with the C-D nozzle system. The result shows that dehumidification enhances as NPR increases. This is due to the high intensity in the turbulence caused by the shock formation in the divergent section. Such disturbance strengthens the centrifugal force, pushing more particles toward the near-wall region. In return return, the pressure recovery factor, defined as the ratio of the outlet static pressure of the fluid to its inlet value, decreases with NPR.

**Keywords**—Supersonic nozzle, dehumidification, particle separation, geometry.

## I. INTRODUCTION

SOLID particles and liquid droplets could form during expansion process of natural gas as a result of temperature reduction. These unpleasant tiny particles could cause severe problems to the carrier means, instrumentations, and flow transmission itself. Blockage could occur following sequential steps of deposition of the non-gaseous particle on the pipe wall. Such blockage increases the possibility of a reduction in flow pressure. The consequences could be even worse if the accumulation grows, resulting in a descent in transmission efficiency and pipe rupture. In such essence, those particles require reliable equipment to remove them. Filtration could only capture particles at size of several micrometers and larger. Submicron and nano size particles will escape the scrubber. Hence, they require reliable means to make the removable process more efficient. Such problems, among many others, have compelled researchers to look for other tools of particle removal from natural gas stream; however, conventional equipment that currently in use are lacking reliability due to the incapability of performing the purification process at minimum problems [1].

Supersonic nozzle is commonly used in gas processing technology to remove tiny droplets and particles that form during gas expansion [2]. It has proven to be firm and robust to use as an alternative particle separation devices for its capability to perform the process more efficiently. Also, the

supersonic-high technology has many advantages as compared with old technologies. It can

- separate small size of the hydrocarbons from natural gas.
- decrease space requirements,
- increase portability,
- decrease handling,
- decrease installation costs,
- decrease costs of operating,
- cause no harmful impact on environment, and
- make no demand for routine maintenance

Okimoto and Brouwer [3] experimentally proved that using supersonic nozzle in gas purification could save up to 20% compressor power compared to current conventional equipment. This may be attributed to the fact that acceleration gained by the particle passing through the shock is huge – close to the order of  $10^6$  times gravity acceleration [4].

Measurements recorded from experiments showed that supersonic nozzles have privilege over other devices [5]. Its compatibility, energy consumption, and high flow speed mitigate the particle mobility and prevent deposition, making them favorite in capturing tiny particles. Moreover, the total pressure of the natural gas will be recovered due to the formation of the shockwave in the divergent portion of the system [4].

Xingwei et al. [6] explored the separation mechanism and heat transfer inside a supersonic separator. Their simulation outcome could be utilized as a cornerstone in designing of a supersonic separator.

Abdi et al. [7], in their comprehensive contribution, presented two examples of CFD applications in natural gas processing and transportation. Their results showed that divergent geometry of the crack changed the flow from subsonic to supersonic flow. Hence, irreversibility was clearly affecting the properties of the flow through the crack. The temperature varies according to the impinging phenomena in both shapes. However, the temperature difference between the jet and THE adjacent wall was relatively higher in divergent shape than the convergent. Additionally, heat exchange due to collision of the jet with the adjacent storage tanks showed significant effects on the temperature distribution.

Yang et al. [8] investigated the gas swirling separation characteristics in supersonic velocities using the Reynolds stress turbulence model. Their results showed that the Laval nozzle designed with the cubic polynomial and Foelsch's analytical methods formed an extremely stable and uniform supersonic flow. However, the supersonic flow was quite sensitive to the delta wing, which led to the disturbance and non-uniformity of the gas dynamic parameters. The variation

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in the supersonic flow had a secondary action on the condensation, resulting in the re-evaporation of the condensed liquids. The delta wing generated a strong swirling flow with the centrifugal acceleration of around  $10^7$  m/s<sup>2</sup>, which provided a strong force to separate the condensed liquids from the mixtures.

## II. EXPERIMENTAL SET-UP

Fig. 1 illustrates a pilot scale dehumidification test-stand system to study the impact of nozzle geometry on the process of separation. The working fluid selected is air. The rig consists of filters, instruments and metering humidifying section as well as C-D supersonic with separation device.

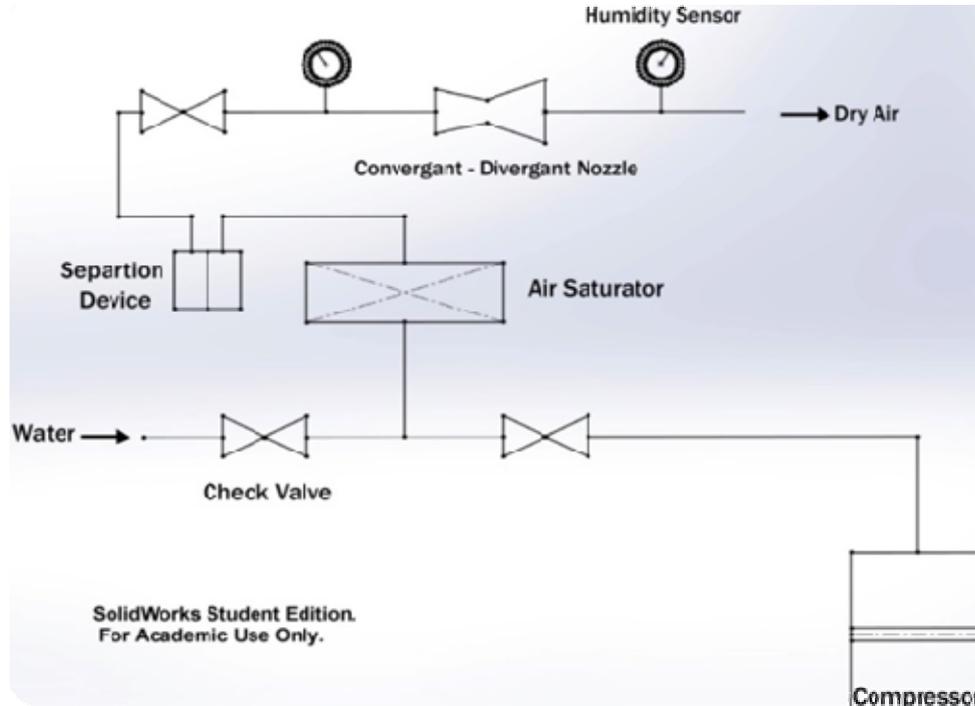


Fig. 1 Particle separation test rig

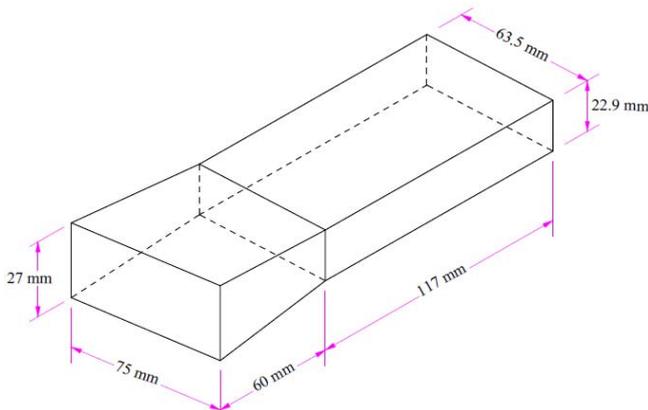


Fig. 2 Schematic and dimensions of the Rectangular Nozzle

The geometrical details of the rectangular nozzle, illustrated in Fig. 2, are presented in Table I. A nozzle with an inlet hydraulic diameter of 39.71 mm and a 33.66 mm exit diameter is selected, such that the ratio of the outlet-to-throat area is 1.4, as seen in Table I. The distances from the nozzle inlet to the nozzle throat and from the nozzle throat to the nozzle exit are selected to match available experimental data.

The outcome of the numerical simulation performed for the 3-D convergent-divergent nozzles concludes that the

separation equipment should be mounted near the throat when the NPR is relatively small [9]. Hence, we relied on this conclusion during construction of the nozzles.

TABLE I  
 DIMENSIONS OF THE CONVERGENT-DIVERGENT NOZZLE

|                           |                      |
|---------------------------|----------------------|
| Inlet area                | 2025 mm <sup>2</sup> |
| Exit area                 | 1454 mm <sup>2</sup> |
| Throat dimensions         | 53.7x19.4 mm         |
| Exit to throat area ratio | 1.4                  |
| Length of Convergent Part | 60 mm                |
| Length of Divergent Part  | 117 mm               |

## III. MOISTURE AIR PRODUCTION TEST STAND

The main components of the system, shown in Fig. 1, are: Compressor, pressure regulator, air moisture, water droplets separator, and check valves. The following describes the function of each part:

- Compressor provides a dry compressed air.
- Pressure valve is a device used to allow high-pressure air-supply to drop to the safe limit.
- Air Moisture Tank is a vessel partially filled with water used to humidify the air stream.
- Water Separator: Any water droplet carried by the air stream that leaves the moisture tank is trapped in the water separator device.

- Check valve: A one-way direction valve allows fluid stream to flow forward but not backward.

The compression system is tested for air/water leakage at connection, air pressure at various spots, and air moisture right after the water separator device to ensure high air humidity before assembling the Supersonic Nozzle System.

#### IV. SUPERSONIC SEPARATION SYSTEM

The nozzle system is composed of three parts: Convergent conduit, separation equipment, and divergent conduit. The convergent part is responsible for expanding the wet feed air stream to the supersonic speed, resulting in a drop in the stream pressure and temperature to the limit of condensation. The separator is used to generate a highly swirling flow, forcing the non-gaseous particles to flow near the wall. The separation part extracts the non-gaseous particles, including the condensed droplets, from the air stream and directs them toward the drain exit. After the dehumidification process, the air stream is headed to the divergent part. The divergent part works as a diffuser and is used to slow down the speed and recover some of the initial pressure.

#### V. EXPERIMENTAL RESULTS

The main themes of the experiments are to determine the performance and the Pressure Recovery Factors of the various geometries of the supersonic separator at different NPRs. Hence, prior to each test, the inlet parameters, including temperature, pressure, relative humidity, and dew point, are set to the prescribed values.

The pressure, temperature, relative humidity, and dew point at the outlet of the supersonic system are recorded for a given NPR. Then, the moisture of the air leaving the diffuser is measured and recorded as the outlet air humidity. The following formula was employed to calculate the separation efficiency:

$$\eta_{separation} = \frac{\omega_{in} - \omega_{out}}{\omega_{in}} \quad (1)$$

where  $\eta_{separation}$  is the separation efficiency of the nozzle system;  $\omega_{in}$  and  $\omega_{out}$  are the moisture content at nozzle's inlet and exit, respectively.

Since the CFD outcome proved that the shock location varies once NPR changes, we repeated the tests of each nozzle for different NPRs. Fig. 3 illustrates how the particle collection efficiency responds to the NPR. Although the triangular shape has the highest efficiency at high NPR, as stated earlier, the circular nozzle; however, leads the separation performance at relatively small and moderate NPRs. The pentagonal shape has the poorest behavior among others for all NPRs.

Next, the behavior of each nozzle shape at different NPRs is experimentally studied. Surprisingly, the circular shape was found to be the best among others in regaining the pressure at

a low NPR, as seen in Fig. 4. Apparently, the shear friction near the nozzle wall region is the prominent factor that prompts unpredictability in the pressure recovery of the nozzle geometries.

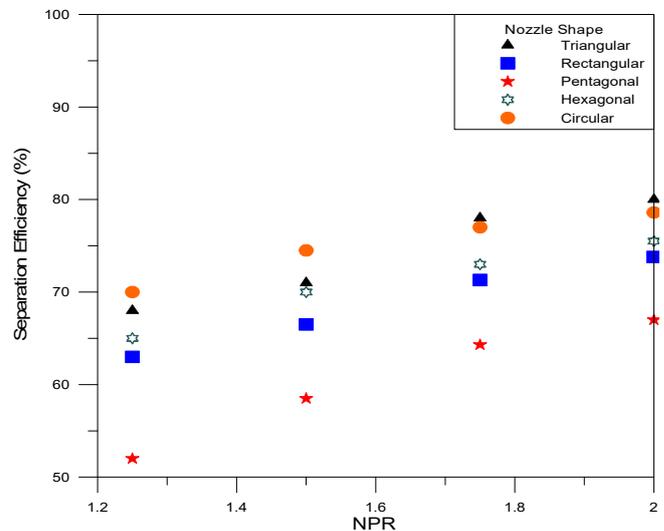


Fig. 3 Comparison of different nozzle shapes at various NPRs

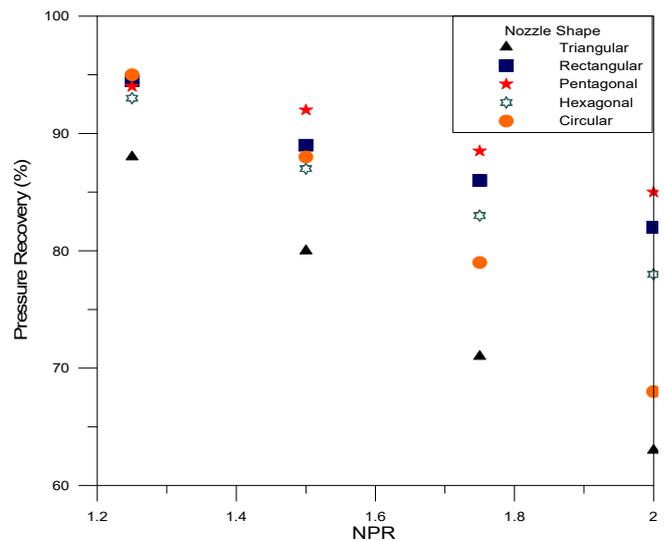


Fig. 4 Pressure recovery factor at different NPRs

#### VI. CONCLUSION

A lab scale apparatus has been built to study the dehumidification performance of supersonic nozzle using moisture air.

The result shows that geometry of the nozzle has significant impact on the separation process. Conical shape was observed to be the best at low NPRs. However, at relatively large NPR, triangular nozzle becomes more efficient. The outcomes also depict that dehumidification of moisture air enhances as NPR increases. Apparently, the shock induced in the divergent portion of the supersonic nozzle produces substantial magnitude of turbulence. Such intensity forms huge

centrifugal force, pushing more droplets toward sublayer region.

In return, the pentagonal shape recovers the air pressure after shock inception better than the others. Also, the pressure recovery factor decreases as NPR increases, raising the losses in the fluid pressure as leaves the supersonic nozzle system.

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