Numerical simulation of a supersonic separator

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Abstract. The current paper presents data on supersonic flow simulation process. The main goal of the study was to demonstrate supersonic separation technology with the help of computational fluid dynamics. In order to determine the quality of separation process itself a supersonic separator has been designed and numerically simulated. The study is mainly concentrated on investigation of the flow structure in the supersonic separator. As a result of the calculation, effective separation factor has been determined, separation process is qualitatively evaluated and described, flow simulation process is visually presented.

1. Introduction
The removal of liquids and solid particles is a significant point for the refining process of natural gas. Supersonic gas separation is an up-to-date technology, mainly used for natural gas dehydration and based on cyclonic separation technique [1-5]. A typical design of a supersonic separator (3S-separator) includes a Laval nozzle, by which supersonic speeds of the flow are reached, a swirler, which is used to generate a strong swirling flow effect, and a diffuser, which allows to convert some part of kinetic energy of the flow into potential, due to braking, and provides a significantly higher gas pressure at the outlet of the diffuser than the static gas pressure in a supersonic nozzle, at which the target components are condensed [6].

While a Laval nozzle is usually used to accelerate the gas to supersonic velocities, resulting in a low temperature and pressure for condensation of water or gas vapor and other types of liquids and flow system components, a swirling device produces a vortex effect [7], creating a strong centrifugal forces field to separate the components.

Comparing to traditional gas separation and refining methods, there is a range of advantages of 3S-separators, such as small size of the apparatus, design simplicity, convenience of transportation and installation etc [8].

One of the key aspects affecting the successful development of 3S-technologies is the possibility to provide effective operation of 3S-separators for unsteady conditions including changing of gas flow rate, which is explained by dynamic technological parameters change, depending on the season during the exploitation [9].

In the current study, the flow structure in a supersonic separator is analyzed and the flow parameters are qualitatively and visually evaluated. According to the complexity of supersonic separation process the studies are more focused on flow simulation using computational fluid dynamics (CFD). In order to calculate efficiency of the apparatus as the most important output parameter, characterizing the quality of separation of gas mixture, a so called effective separation factor is introduced. Separation factor
presents the mass flow rate ratio of the separated particles in the outlet and total number of particles in the inlet respectively, which are obtained from the calculation statistics.

2. Mathematical Model

2.1 3S-separator design
A non-standard structure of a 3S-separator has been designed taking into account calculation domain is gas, mainly methane (96%) and impurities concentration is supposed to be 5 mg/m³. The apparatus consists of such main parts as a swirler, Laval nozzle, workspace and diffuser (figure 1). One of the most significant features of the separator is the swirler type. The swirler represents a screw with a variable pitch of spiral threads (table 1). The swirler structure provides a good swirling effect after the flow exits the screw and enters the Laval nozzle according to the gas-dynamic resistance values obtained from experimental data.

| Thread length, mm | Turn | Height, mm | Diameter, mm |
|-------------------|------|------------|--------------|
| 100               | 0    | 0          | 100          |
| 100               | 1    | 100        | 100          |
| 90                | 2    | 195        | 100          |
| 80                | 3    | 280        | 100          |
| 70                | 4    | 355        | 100          |
| 60                | 5    | 420        | 100          |
| 50                | 6    | 475        | 100          |

Figure 1. Construction of a 3S-separator for numerical calculation.

2.2 General Equations
While passing through the Laval nozzle low values of temperature and pressure conditions are reached in the domain. In order to describe the fluid structure of the natural gas flow there are conservation equations of mass, momentum, energy and continuity that could be written in general form, shown in eqn (1) – (4) respectively [10].

The continuity equation for phase \( q \) can be written as:
\[
\frac{\partial}{\partial t} (\alpha_q v_q) + \nabla \times (\alpha_q p_q \vec{v}_q) = \sum_{p=1}^{n} (\dot{m}_{pq} - \dot{m}_{qp}) + S_q, \tag{1}
\]

where \(\vec{v}_q\) is the velocity of phase \(q\); \(\dot{m}_{pq}\) characterizes mass transfer from phase \(p\) to phase \(q\) and \(\dot{m}_{qp}\) characterizes mass transfer from phase \(q\) to phase \(p\) respectively. Both of the mechanisms can be specified separately.

The momentum balance for phase \(q\):
\[
\frac{\partial}{\partial t} (\alpha_q p_q \vec{v}_q) + \nabla \times (\alpha_q p_q \vec{v}_q \vec{v}_q) = -\alpha_q \vec{v} \times \vec{\tau}_q + \alpha_q p_q \vec{g} + \sum_{p=1}^{n} (\vec{R}_{pq} + \dot{m}_{pq} \vec{v}_q - \dot{m}_{qp} \vec{v}_p) + (\vec{F}_q + \vec{F}_{\text{lift},q} + \vec{F}_{\text{v.m},q}), \tag{2}
\]

where \(\vec{\tau}_q\) is the stress-strain tensor of phase \(q\).

In order to describe conservation of energy in Eulerian multiphase systems, there is an enthalpy equation that could be written as:
\[
\frac{\partial}{\partial t} (\alpha_q p_q h_q) + \nabla \times (\alpha_q p_q \vec{u}_q h_q) =
\]
\[
= \alpha_q \frac{\partial p_q}{\partial t} + \vec{\tau}_q \cdot \vec{v} \vec{u}_q - \vec{v} \vec{u}_q - \vec{v} q + S_q + \sum_{p=1}^{n} (Q_{pq} + \dot{m}_{pq} h_p - \dot{m}_{qp} h_q) \tag{3}
\]

where \(h_q\) is the specific enthalpy of phase \(q\); \(\vec{\vec{q}}\) is the heat flux; \(S_q\) is a source term that includes source of enthalpy; \(Q_{pq}\) is the intensity of heat exchange between phases \(q\) and \(p\); \(h_{qp}\) is the interphase enthalpy.

The continuity equation can be represented as:
\[
\frac{1}{\rho_{rq}} \left( \frac{\partial}{\partial t} (\alpha_q p_q) + \nabla \times (\alpha_q p_q \vec{v}_q) = \sum_{p=1}^{n} (\dot{m}_{pq} - \dot{m}_{qp}) \right), \tag{4}
\]

where \(\rho_{rq}\) is the phase reference density, or the volume averaged density of phase \(q\) in the solution domain.

Since natural gas contains dispersed phase in the domain representing water droplets ans solid particles, there is also discrete phase transportation equation, which is written as:
\[
\frac{d\vec{u}_d}{dt} = F_d (\vec{u} - \vec{u}_d) + \frac{\rho - \rho_d}{\rho_d} \vec{g} + \Sigma \vec{F} \tag{5}
\]

### 2.3 Turbulence Model

The Reynolds stress model (RSM) is one of the most improved turbulence models CFD software suggests. RSM requires solution of transport equations for the Reynolds stresses and and equation for the dissipation rate \([11]\).

Taking into account the fact RSM model is perfectly suitable for calculating effects including curvature, swirling and rotational moments, plus, strain rate rapid changes, it is able to give accurate predictions towards solving vortex effects for the supersonic separation process \([12]\). RSM offers 7 equation which are a part of modelling turbulent diffusive transport, pressure-strain term, effects of
buoyancy on turbulence, turbulent kinetic energy, dissipation rate, turbulent viscosity and convective heat and mass transfer modelling [10].

2.4 Boundary Conditions Description
Since the whole calculation domain is supposed to be initialized from the inlet, boundary conditions are the inlet velocity (5 m/s), pressure (85 atm) and temperature (280 K) are determined as initial values. Outlet parameters of the flow are calculated automatically.

In order to obtain near-wall condensate and particles distribution, Lagrangian wall film has been set up as one of the boundary conditions. Talking about boundary layer and near-wall effects, calculation mech includes inflation method with a number of 10 layers and Growth Rate of 1,2. No slip and adiabatic boundary conditions were specified for the walls.

In the case of this modelling the finite volume method was adopted as COUPLED algorithm.

3. Results Discussion
The characteristics of the flow were numerically simulated and visually evaluated. According to figure 2, the swirling effect is demonstrated in the whole calculation domain of the separator.

![Figure 2. The swirling effect.](image)

Under the influence of the swirling effect, gas condensate and solid particles are brought to the periphery in the duffuser’s inner walls under the action of high values of tangential velocities of the flow. It is worth paying much attention to the boundary layer since near wall area appears to collect the components separated out of the target gas stream transforming the initial natural gas flow into dry gas and a wall film containing solid and liquid components, which is concentrated on the inner walls.

Wall film and separated components concentration on the inner walls has been analyzed (figure 3)
Figure 3. Separated components concentration (volume fraction) in the near inner walls area: a – cross-sections in the screw swirler location; b – cross-sections in the diffuser location.

As it is seen from figure 3 due to the strong vortex effect and high values of tangential velocities of the flow gas condensate and solid particles mixture are forming a tightly packed layer mainly on the inner walls of the workspace and the diffuser. High values of tangential velocities are not observed in the screw swirler location due to weaker swirling action of the gas flow and much lower velocities, thus strongly marked wall film of the separated components is absent. The separation process itself is forming right after the Laval nozzle when the flow acquires both high values of velocities and the vortex factor.

According ton analysis of the components mass flow in the inlet and outlet, averaged effective separation factor (ratio) is about 98 %.

4. Conclusion
The main objective of this paper was to study the structure of the flow in a supersonic separator and demonstrate the quality of the multiphase mixture separation technology by means of numerical simulation.

As a result of the numerical simulation of the supersonic separation process there are characteristic tangential velocities of the flow that have been evaluated for a non-standard structure of a 3S-separator containing an unusual type of a swirler represented as a screw.

Averaged separation ratio is gained which is 0,98, that appears to be about 1,5 more than an average separation ratio for cyclone separation systems.

Separated components are concentrated on the inner walls of the diffuser mainly, forming a dense layer. Next studies on the 3S-separation technology will contain information about development of a method for utilizing the components out of the inner space of the separator.

To sum up, visual representation of supersonic gas flow has been obtained with the help of CFD. Since current study is the first step towards developing a new supersonic separation technology and the corresponding design of a 3S-separation, further calculations will make the appropriate adjustments for the current results.

Numerical calculation shows the importance of unknown phenomenon and effects simulation in order to make the first step towards further scientific based development of any industrial problem.
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