Computational Fluid Dynamic Modelling of a Gas-Motive, Liquid-Suction Eductor for Subsea Gas Processing Applications

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Abstract

Much of the world's remaining undeveloped gas resources are found in deep water and require seabed / subsea developments to be economic. At these depths, the typically high pressures and low temperatures form the necessary conditions for hydrate formation. At start-up, and in some cases in steady state flow, hydrate inhibitors (generally monethylene glycol, MEG) have to be injected at the wellhead to prevent hydrate formation. The traditional way to deliver MEG to a wellhead is via a flowline from the nearest installation - but as distances between wellhead and installation rise, this is becoming prohibitively expensive. As an alternative, it has been proposed that if a MEG tank was placed on the seabed, MEG could be sucked into the flowline at the wellhead using an eductor, which utilizes the energy from high pressure of the well to entrain the MEG. This purpose of this project is to assess the feasibility of concept by quantifying the operational envelope for a possible seabed eductor – and in particular, to explore how much MEG can be drawn into the flowline and to assess whether this is sufficient to prevent hydrate formation. To achieve this, Computational Fluid Dynamics is being used to predict the performance of an eductor for given inlet pressure (wellhead), outlet pressure (flowline back pressure) and static MEG tank pressure.

1. Introduction

1.1 Background

Natural Gas Hydrate prevention and remediation is one of the most difficult challenges to resolve in the oil and gas industry. This research investigates the delivery of hydrate-inhibiting monoethylene glycol (MEG) to a subsea pipeline through the use of an eductor (also commonly referred to as jet pumps, ejectors, venturi pumps and jet compressors in the literature). Eductors are devices that use the energy within a high-pressure fluid to entrain and compress a low-pressure fluid to an intermediate pressure (Transvac, 2013) – but the proposed application is a significant extrapolation from their normal mode of operation.

1.2 Project scope

This project investigates the feasibility of a subsea eductor to entrain hydrate-inhibiting MEG into the production pipeline using high-energy wellhead gas stream as the motive force. It will seek to determine the amount of MEG that can be entrained by a seabed eductor for a given set of wellhead pressure, outlet pressure (flowline back presssure) and static MEG tank pressure. This eductor 'data-cube' can then be implemented in Olga or other simulation software to assess specific systems where seabed eductors are being considered.

This analysis uses ANSYS Fluent™ CFD software as the primary tool for modelling eductor performance.

1.3 Current Practice

Traditional MEG infrastructure involves running MEG supply lines from the nearest installation to every wellhead in a subsea gas development. Typically, there is a dedicated line for delivering MEG, and a 'utility' line, which is used to enable double-sided blowdown in case of a hydrate blockage. This style of configuration is common to many offshore gas projects undertaken in Australia, and as distances from installation to wellheads, and number of wellheads increase, these costs become significant.

1.4 Proposed Configuration

Technology improvements in the insulation and electrical trace-heating of subsea pipelines to keep the gas product above the hydrate-forming zone have been investigated with the aim of reducing the need for MEG during steady-state conditions. In an ideal configuration, the pipe insulation is sufficient to maintain the fluid temperature to prevent the need for any continuous MEG injection during steady state, thus eliminating the need for the capital-intensive MEG infrastructure (Patrick, 2014).

A previous study (Patcik, 2014) has shown that during transient conditions (low or no-flow during start-up & shut-down) the insulation of the pipeline will be insufficient, and some MEG injection will still be required until steady state is reached. The concept of having a dedicated MEG supply line just for start-up is thus being challenged, and in accordance with the preceding CEED project, it is proposed that the MEG required for transient conditions will be provided via the umbilical, and stored locally in a subsea unit. The precise configuration is not important to this project – what is being tested is whether MEG stored in a local tank can be satisfactorily drawn into the flowline using the wellhead pressure.

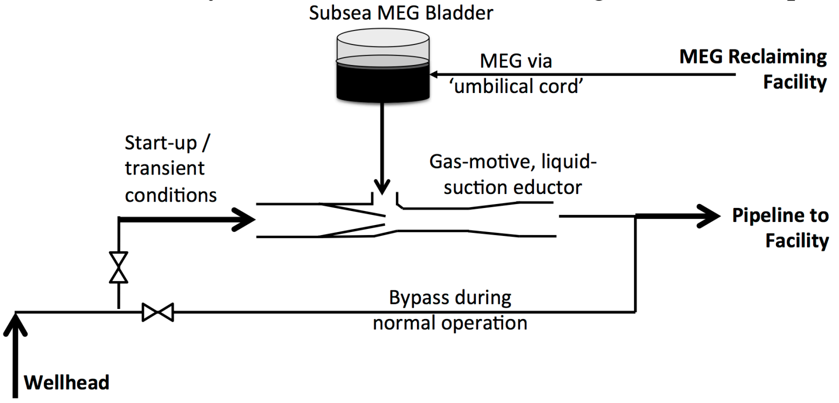


Figure 1 Configuration of the proposed system

If the MEG storage / eductor concept proves feasible, further works will be needed to examine the type of subsea storage, the supply method of MEG (continuous trickle, or swap-and-replace storage tanks) and the operational risks incorporated with this configuration.

1.4 Benefits Analysis

If the project is successful, capital and operating expenditures can potentially be reduced. A deep water gas field MEG pipeline supply system, which may support tens of wells, and the associated infrastructure (manifolds, branches, control equipment etc.) is expensive and can difficult to lay and maintain (particularly in deep water or in uneven bathymetric conditions). Furthermore, the eductor system, when used in conjunction with insulation and/or electrical trace heating technologies preventing the need for MEG injection in steady state, will also use considerably less MEG than a conventional system.

In addition to saving long-distance pumping costs, the proposed configuration also makes use of energy that is currently being 'destroyed' at the wellhead (flow-limiting) choke valve in conventional installations – so the overall energy footprint is also improved.

2. Eductor Theory

Eductors are widely used in process industries and particularly in steam / water service (they were invented to draw water into the pressurised steam boiler of steam trains). As more cost effective solutions are being sought for offshore gas field developments, eductors are being promoted (Transvac, 2013) due to the absence of pistons, valves, rotors or other moving parts (Perry, 2008). It is suggested that they should be easy to operate, have long lives, sustained efficiency and lower maintenance costs (McCabe et al., 2004). They have been trialled in subsea applications as a method of boosting the production of low-pressure gas wells by drawing on nearby high-pressure wells, with promising results (Chen et al., 2011) (Transvac, 2013) but their application at this time is limited. A number of companies now specialize in the design, experimental validation and sale of subsea processing eductors [ejectors] such as Transvac, Jacobs and Caltec.

As illustrated in Figure 2, an eductor works by directly entering (high pressure) fluid through a converging nozzle, increasing its velocity and decreasing its pressure as per Bernoulli's Principle (Balamurugan et al., 2006). To get an eductor to 'suck', it is necessary for gas velocities in the nozzle to be as high as possible and it is common for the nozzle to be in choked flow, resulting in supersonic velocities following the nozzle. As the high-velocity jet moves outwards from the nozzle, it will create a radial inflow such that some kinetic energy is transferred to the surrounding fluid, causing a suction effect (Balamurugan et al., 2007). The two streams mix in the diffuser, and pressure is 'recovered' in the diverging section as the velocity of the mixture slows. The resulting combined flow is at an intermediate pressure value between thoset of the two inlet streams (Transvac, 2013), (Liu & Groll, 2008).

There are a number of fluid combinations that can be used in eductors for the given motive and suction fluids (motive-suction): liquid-liquid, liquid-gas, gas-liquid and gas-gas. For single-phase, eductors there are well-established models for performance analysis and design calculations (Keenan et al. 1950; Munday and Bagster 1977; Huang et al., 1999). However, for two-phase flow eductors, particularly at the pressures being contemplated for gas field /

seabed service, there are no established models (Liu & Groll, 2008) and little empirical data is available for model calibration.

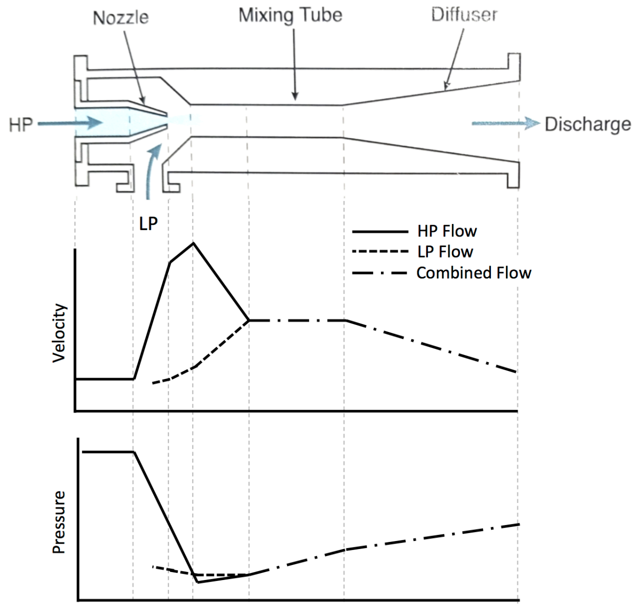


Figure 2 The typical axial pressure and velocity profile (Caltec, 2012)

Most studies of gas-liquid systems consider basic pairings such as air-water, N2-water or steam-water. Despite this, some studies (Watanawanavet, 2005) (Cunningham et al., 1974) have extended their results to include dimensionless groups, enabling their application to different fluid combinations and process conditions.

2.1 Theory Fundamentals

For a given upstream pressure (P_1), the rate of discharge of gas from a nozzle will increase as the downstream pressure decreases (P_2) until the linear velocicty in the throat reaches that of sound in the gas at that location. The value of P_2/P_1 for which sonic velocity is just attained is called the critical pressure ratio r_c. The actual pressure in the throat will not fall below $p_1 r_c$ even if much lower pressure still exists downstream (Perry, 2008).

$$P_c = P_1 \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} \tag{1}$$

where P_c is the critical pressure, P_o is the upstream pressure and γ is the heat capacity ratio c_p/c_v of the gas. For methane we substitute $\gamma = 1.31$ and obtain the following:

$$P_c = 0.544 P_1 \tag{2}$$

Thus, in order to obtain the maximum jet velocity – hence the highest momentum for potential transfer to the entrained flow – it is important for the pressure downstream of the nozzle to be low enough to induce choked flow. When designing the eductor, it is important to consider what nozzle size will be able to accommodate the full desired flowrate of the well. In choked flow the mass flow rate is given by:

$$\dot{m}_{max} = CA^2 \sqrt{g_c \gamma (\rho_1 P_1) \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{3}$$

where $\dot{m}$ is the mass flow rate of the gas (kg/s), C is the coefficient of discharge, A is the nozzle throat cross sectional area (m^2) g_c is a dimensional constant and v is the upstream velocity (m/s)

2.2 Development of the eductor model

The development of the eductor model has been produced in stages as shown below. The progression started with simple gas-gas eductor systems – which have been shown to be operating correctly – with current modelling now moving on to gas-MEG eductor systems. Each step adds an additional layer of complexity to the model.

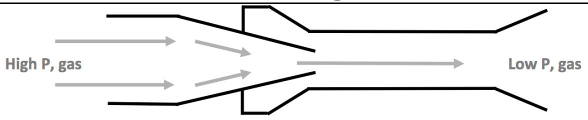
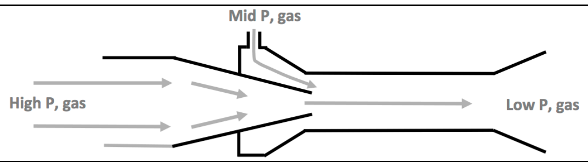
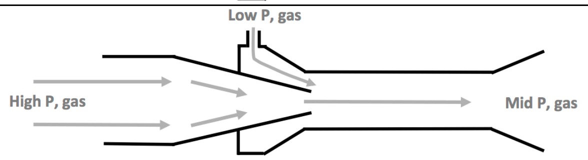
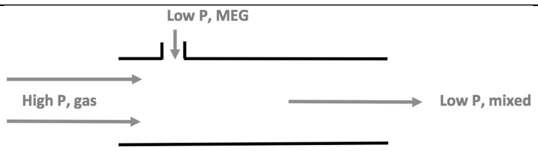
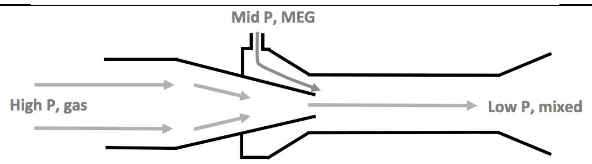
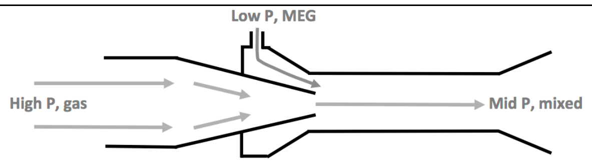
#	Model Diagram	Goals
1		1 inlet, single phase, flow reaching choking condition at nozzle inlet
2		2 inlet, single phase, with a 'driving' pressure gradient i.e. $P_{suction} > P_{outlet}$
3		2 inlet, single phase, **no** 'driving' pressure gradient $P_{suction} < P_{outlet}$
4		2 inlet, multiphase flow
5		2 inlet, multiphase flow, with 'driving' pressure gradient
6		2 inlet, multiphase flow, with **no** 'driving' pressure gradient

Table 1 Model progression plan

3. Results and Discussion

Of the table above, model progression numbers 1, 2, 3 and 4 have been successfully completed, with further optimization still undergoing. Due to space limitations, only the results and prevailing conditions from model number 3 are shown below. This model was significant as it is successfully 'sucking' the LP stream into the HP stream (i.e. the velocity of the high pressure gas is being used to induce the lower pressure gas)

For an eductor to work effectively – and to convert the kinetic energy of the high pressure gas to create suction, there needs to be a careful balance between the nozzle size (motive velocity), mixing tube diameter, mixing tube length and the specified boundary conditions (BC). The nozzle size and inlet-outlet pressure ratio needs to drive a velocity (i.e. kinetic energy) sufficient enough for the length of the mixing tube length, whilst the mixing tube diameter must be small enough to prevent fluid leaking back into the system (Watanawanavet, 2005)

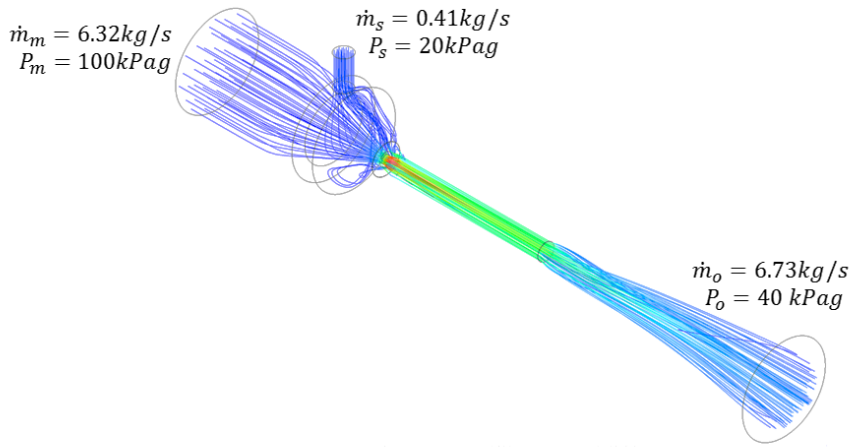


Figure 3 Streamline velocity profile

4. Conclusions and Future Work

The work completed so far has found that when set-up properly, the software is able to successfully model the behaviour of a gas-gas eductor with promising entrainment performance. The stability of the model has found to be strongly dependent on the geometry and the boundary conditions chosen.

Currently model 3 is being re-run with pressures closer to the intended subsea application $100\ bar < P_{motive} < 400bar$ and $5bar < P_{suction} < 20bar$ (represents 50-200m water depths). Further optimization of the geometry will be required to ensure that sonic flow is reached at the nozzle exit, and boundary layer separation is not occurring in the mixing tube or diffuser. Construction of models 5 and 6 are well underway, using updated geometries from previous models. The target 'data-cube', represents a matrix of the amount of MEG that can be entrained by a seabed eductor for a given wellhead, outlet (flowline back pressure) and static MEG tank pressure, will be generated by model 6.

5. References

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