CFD Modelling of Inline Contacting of MEG at Low Temperature

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Abstract

The development of offshore gas fields by long distance subsea tie-back together with subsea processing presents a wide range of opportunities. The dehydration of the natural gas stream is a critical stage in mitigating the risk of hydrate formation and pipeline corrosion. One method to achieve successful subsea dehydration at lower temperatures involves contacting the natural gas with monoethylene glycol (MEG) within an inline contactor. The atomisation of the liquid MEG jet within the inline contactor increases interfacial area, leading to enhanced mass transfer of water vapour. The objectives of this project include characterising the atomisation of a liquid MEG jet within an inline contactor using Computational Fluid Dynamics (CFD) and modelling the contacting performance of the subsequent flow field using a 1D thermodynamic flow model.

CFD models replicating liquid jet spray experiments were constructed to validate the CFD approach. The CFD validation found the k-ε turbulence closure model to be more accurate than the k-ω and SST k-ω models. CFD models predicting MEG jet atomisation have highlighted the importance of the momentum flux ratio in addition to the Reynolds and Weber numbers. Quantification of water vapour transfer was achieved by creating a three-fluid, 1D flow model. The results of the 1D flow model reveal the initial droplet size distribution and gas phase velocity are the primary factors governing contactor length.

1. Introduction

Natural gas dehydration is an important step in minimising hydrate formation and pipeline corrosion which may lead to flowline failure by blockage due to hydrate deposition or loss of integrity. Natural gas dehydration is typically achieved through the use of triethylene glycol (TEG) within a vertical contacting column at a topside or shore based facility. The recent interest in subsea processing across the oil and gas industry prompts alternative methods for natural gas dehydration, primarily due to the low ambient temperatures in the subsea environment resulting in prohibitively high TEG viscosity.

Subsea gas dehydration takes advantage of low subsea temperatures by first cooling and separating majority of the liquid water from the gas stream, often with the assistance of monoethylene glycol (MEG). To remove additional water vapour and satisfy export pipeline specifications, it is proposed that the resulting gas stream be passed through an inline contactor where it is contacted with MEG (introduced as a spray of droplets). After having reached contacting equilibrium, the rich MEG is disengaged from the gas stream and regenerated. Figure 1 depicts the configuration of the inline contactor arrangement.

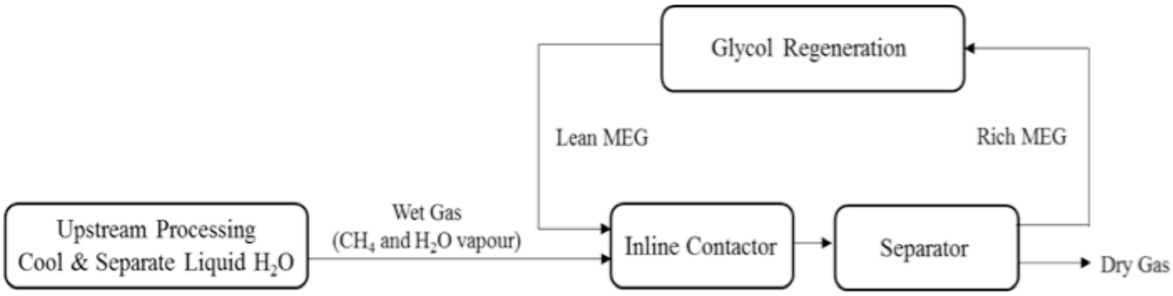


Figure 1 Proposed subsea natural gas dehydration using an inline MEG contactor.

The exact breakup process of the injected MEG jet and the impact of low ambient temperature on MEG contacting are currently not well understood. Given the potential for damage and loss of production due to hydrate formation and corrosion, excess MEG is typically introduced into the gas stream to ensure adequate dehydration. In addition to hydrate and corrosion prevention, the benefits of optimised subsea dehydration include cost savings through reduced topside facility footprint and increased contacting efficiency.

1.1 Project Scope

This project sought to characterise the breakup mechanisms of an injected MEG jet in order to gain insight into the resulting droplet field and subsequently quantify the water extracted from the gas stream in the inline contactor. The ANSYS Fluent Computational Fluid Dynamics (CFD) software was utilised to determine the effects of various upstream flow conditions on liquid MEG jet breakup. The performance of the CFD approach was validated against liquid jet spray experiments conducted by Hardalupas et al. (1995). A three-fluid, 1D flow model was then created to quantify the mass transfer process and contactor length required to achieve thermodynamic equilibrium. As the proposed inline MEG contactor is currently within the early stages of development, identification and mitigation of technology risk was also required.

1.2 Literature Review

Underpinning the success of the inline contactor strategy is the extent to which the MEG jet may be atomised. Atomisation refers to the jet breakup regime whereby the average diameter of the resulting droplets are considerably smaller than the initial jet diameter (Lefebvre 1989). Coaxial atomisation, involving a liquid jet surrounded by an annular gas jet, may be broken down into the three successive regions of nozzle effects, primary breakup and secondary breakup (Dumouchel 2008). Figure 2, adapted from Lasheras & Hopfinger (2000), depicts the regions.

The onset of atomisation is largely governed by nozzle construction, with intial perturbations primarily resulting from liquid jet turbulence, velocity profile shapes, potential for cavitation and manufacturing imperfections (Reitz & Bracco 1982). The presence of a coaxial gas stream encourages atomisation through the primary breakup mechanism. The kinetic energy provided by the higher velocity gas stream, coupled with the interfacial instability of the two phases, lead to the formation of ligaments, as shown in Figure 2. These ligaments eventually detach from the bulk of the liquid jet and disintegrate into droplets of varying size (Lasheras & Hopfinger 2000). The secondary mechanism concerns the breakup of larger droplets due to the turbulent stresses induced by the gas stream overcoming the surface tension and internal viscous forces of the droplet (Hinze 1955).

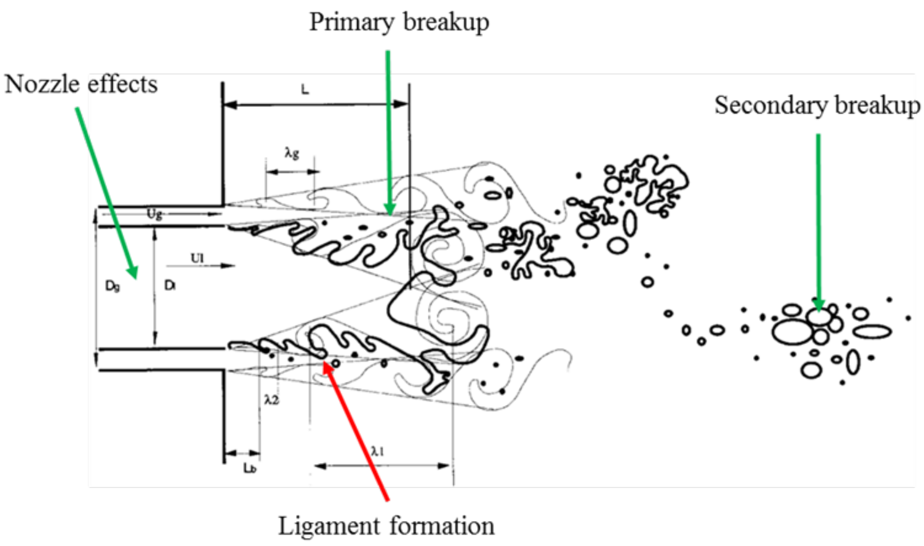


Figure 2 Coaxial liquid jet atomisation (Lasheras & Hopfinger 2000).

Successful multiphase CFD modelling requires methods accounting for topology change over a wide range of length scales. The volume of fluid (VOF) model is one such method which has achieved great popularity due to its ability to inherently conserve liquid volume (Gorokhovski & Herrmann 2008). Fuster et al. (2009) considered the impact of density ratio in primary atomisation through utilising a VOF approach and reported successful resolving of both the linear regime and transverse instabilities of the non-linear regime. Building on the findings of the literature, this project makes use of the VOF model whilst comparing various Reynolds-Averaged Navier-Stokes (RANS) turbulence closure models.

2. Process

2.1 CFD Validation and MEG Injection Models

CFD validation was undertaken for axisymmetric and 3D models using the built-in VOF model of ANSYS Fluent, version 15.0. The validation models replicated the experimental setup of Hardalupas et al. (1995) by considering the breakup of a low velocity water jet (3.6 m/s) due to a surrounding high velocity annular air jet (112 m/s). The objective of the validation was to provide insight into the capacity of the CFD software to predict liquid jet atomisation. Given the criticality of accurately resolving the interfacial shear stress, the k-ε, k-ω and SST k-ω RANS turbulence closure models were tested and compared. Key outputs included the liquid jet breakup length, velocity profiles and turbulence profiles.

The CFD MEG injection models investigated the impact of upstream flow conditions and nozzle pressure drop on the atomisation of a liquid MEG jet under typical subsea conditions. The k-ε turbulence closure model was selected following the findings of the validation results. By changing the diameter of the inline contactor, the relative importance of the momentum flux ratio (MFR), Reynolds and Weber numbers were observed. Two orifice nozzles of varying diameter ratio were tested to assess the impact of pressure drop on liquid jet atomisation. Key outputs included visualisation of the MEG jet atomisation, as well as turbulent kinetic energy and dissipation profiles which allow for the initial droplet size distribution to be inferred.

2.2 Three-Fluid, One-Dimensional Annular-Dispersed Flow Model

To quantify the mass transfer of water vapour from the gas stream to the MEG, a three-fluid, one-dimensional annular-dispersed flow model was created. A hydrodynamic model was first formulated by considering the mass and momentum conservation equations for three fluids, namely the gas core, entrained MEG droplets and annular MEG film located on the contactor wall. Closure models were then selected and a Runge-Kutta method implemented to solve the system of coupled differential equations. The evolution of the droplet field was then inserted into a mass transfer model, which computed the water vapour transfer through experimentally based mass transfer coefficients obtained from the literature. Key outputs of the overall one-dimensional model included the effect of varying MEG flow rate, contactor diameter and droplet size distribution on the length required to achieve thermodynamic equilibrium.

3. Results and Discussion

3.1 CFD Validation Modelling

Figure 3 compares the experimental results of Hardalupas et al. (1995) with the axisymmetric and 3D validation results for the selected set of closure models. For a valid comparison, the CFD validation results should be compared to the 9 μm experimental results to replicate the gas phase turblence and to ensure the lowest possible Stokes number. The 3D validation results more accurately capture the variation in normalised velocity fluctuation when compared to the axisymmetric validation results. This highlights the 3D nature of turbulence and the limitations of modelling liquid jet breakup as an axisymmetric phenomenon. When comparing the turbulence closure models used, the k-ω model exhibits the greatest innaccuracy. Although not shown here, the k-ω model produced significant error when considering the liquid jet breakup length. Analysis of the entire set of validation results suggests atomisation should be modelled in 3D and of the turbulence closure models tested, the k-ε model is most accurate.

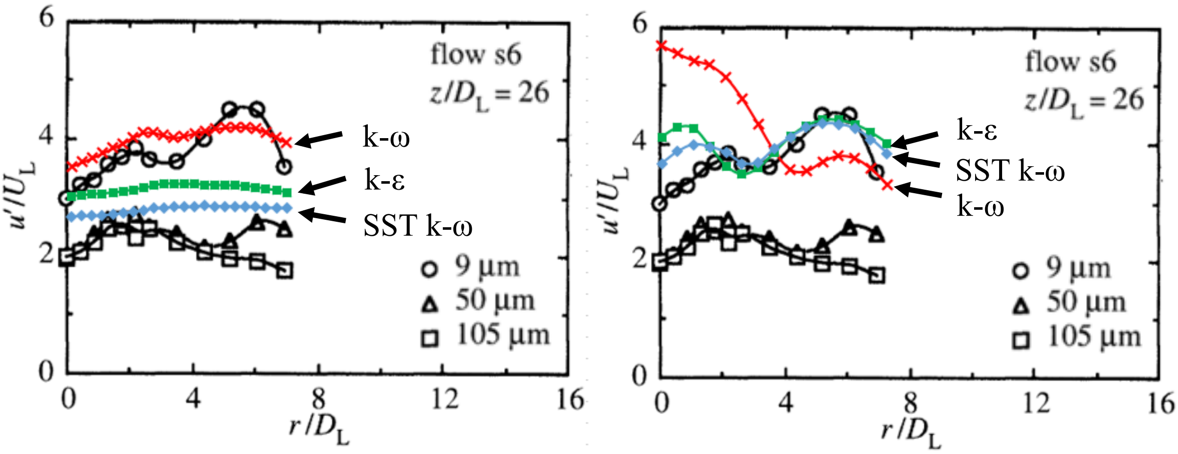
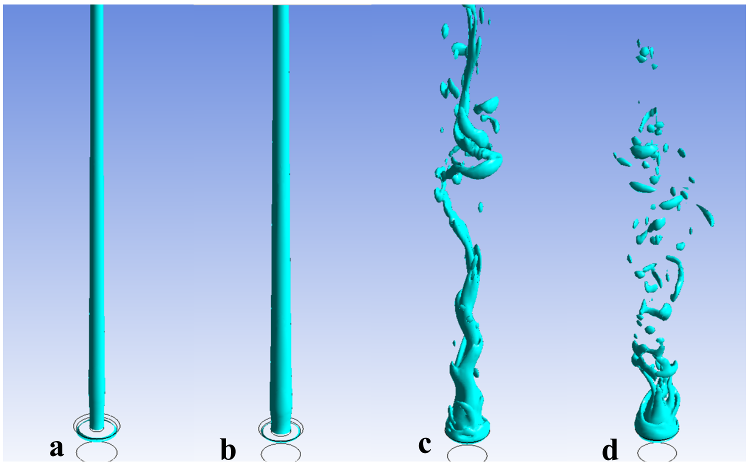


Figure 3 Axisymmetric (left) and 3D (right) normalised velocity fluctuation profiles.

3.2 CFD MEG Injection Modelling

Figure 4 illustrates the MEG volume fraction isosurfaces within the inline contactor for the four CFD cases considered. Figure 4a and 4c depict the MEG jet for orifice nozzles of outlet to inlet area ratios of 0.11 and 0.25 respectively. The MEG jet of Figure 4a shows no sign of breakup, despite the larger liquid Reynolds and Weber numbers. This finding is attributable to the fact the relative velocity between the MEG jet and the gas stream is lower for the case of

Figure 4a, as shown by the smaller MFR value of 0.54. This finding supports the argument that, in addition to the liquid Reynolds and Weber numbers, the MFR is required to adequately characterise jet breakup (Lasheras and Hopfinger 2000). Figure 4b, 4c and 4d represent identical orifice nozzle geometries, with inline contactor diameters of 0.25 m, 0.20 m and 0.15 m respectively. A similar trend is observed with Figure 4d, having the largest MFR of 8.70, displaying the greatest degree of breakup. The CFD findings not only suggest that the MFR plays a critical role in characterising jet breakup, but also the existence of a critical MFR for which breakup initiaites.



MFR = 0.54 MFR = 1.13 MFR = 2.75 MFR = 8.70

Figure 4 MEG volume fraction isosurfaces. MFR = $\rho_g U_g^2 / \rho_l U_l^2$.

3.3 Three-Fluid, One-Dimensional Annular-Dispersed Flow Modelling

Although the CFD results portray greater MEG atomisation with decreasing contactor diameter, the resulting increase in gas velocity leads to a reduction in MEG droplet residence time. This reduced residence time works against the dehydration of the gas stream. However, higher gas velocities correspond to more intense turbulence which assists in the mixing and recirculation of entrained MEG droplets. Figure 5 depicts the gas stream water vapour fraction as a function of contactor length for contactor diameters of 0.15 m, 0.20 m and 0.25 m. By decreasing the contactor diameter, the dehydration curve is seen to shift to the left and approach equilibrium at shorter contactor lengths. This findings suggests that the enhanced mixing due to turbulent effects offsets the reduced residence time when the contactor diameter is decreased.

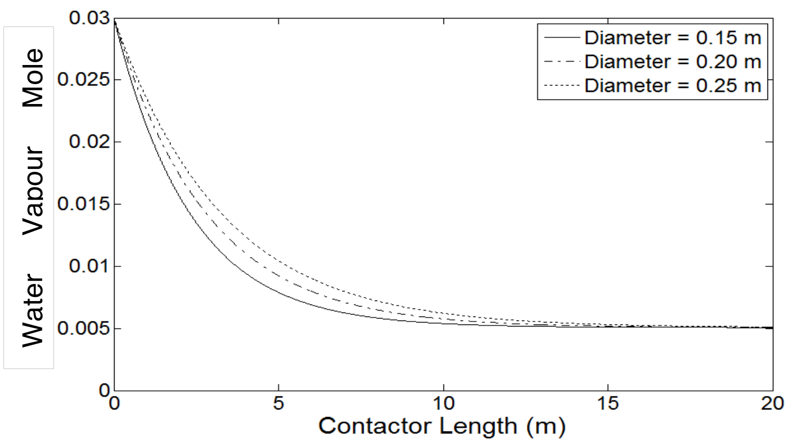


Figure 5 Water vapour mole fractions for varying contactor diameters.

4. Conclusions and Future Work

This paper presents a modelling approach for identifying and mitigating technology risk associated with subsea inline MEG contacting. Given the findings of the CFD validation, it is recommended that a 3D formulation of jet atomisation be adopted in conjunction with the k-ε RANS turbulence closure model. The CFD MEG injection modelling demonstrates the importance of the momentum flux ratio in characterising the breakup of a liquid MEG jet. Use of the liquid Reynolds and Weber numbers alone proves insufficient in predicting the onset of jet breakup. In quantifying the mass transfer of water vapour from the gas stream, a three-fluid, one-dimensional annular-dispered flow model was created. When decreasing the diameter of the inline contactor, it was found that the mixing effect due to turbulence more than offset the reduced MEG droplet residence time, leading to minimised inline contactor lengths.

Future work includes modifying the CFD MEG injection modelling to include non-coaxial or crossflow geometry arrangements. This would enable the CFD approach to assess the feasibility of a wider range of nozzles. Extending the three-fluid, one-dimensional model to a population balance model would allow for additional modelling of droplet breakup and coalescence. Additional work also includes coupling the resultant droplet field of the CFD model to the 1D model.

5. References

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