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Numerical simulation of the flow of supercritical CO_2 in a multistage centrifugal pump

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Abstract
High concentrations of CO_2 in the Brazilian pre-salt reservoirs pose many operational challenges to oil production. To overcome this, several proposals for new technologies are being developed. One of them is the separation of a liquid phase from another dense gaseous (supercritical) phase rich in CO_2 in the seabed. Then, a subsea multistage centrifugal pump could be used to reinject the CO2–rich dense phase into the reservoir. However, it is unclear whether a centrifugal pump would maintain its baseline performance when working with a dense gas instead of a liquid. In this context, the present work aims to evaluate the performance of a multistage centrifugal pump operating with supercritical CO_2 through numerical simulations using ANSYS® CFX®. The flow turbulence is modeled through the $\kappa-\omega$ SST model. Variation of the fluid's thermo-physical properties is calculated through interpolations using a real gas property (RGP) thermodynamic table obtained from the NIST® REFPROP® coupled to the ANSYS® CFX®. The numerical model is validated with experimental data obtained from the pump operating with water. The results from the pump simulations working with supercritical CO_2 at different flow rates, pressure, and temperature at the pump inlet allowed us to build pump performance and fluid-temperature rise curves. With that, it was obtained a first impression about the feasibility of using centrifugal pumps to pump supercritical fluids and information to contribute to the literature on the subject, which is scarce.

Keywords
Centrifugal Pump; Performance curves; Supercritical fluid.

Introduction
One of the main challenges encountered in the Brazilian pre-salt oil and gas fields, in addition to the depth and distance from the coast, is associated with high levels of CO_2. Besides other technical aspects, CO_2 is considered a contaminant that reduces the calorific value of natural gas and has a negative impact on flow assurance as well as environmental concerns. In some fields, CO_2 molar concentration can reach up to 79% in the gaseous fraction [1].

Currently, the technology used in the CO_2 separation and reinjection process, in the supercritical state, is expensive, energy-intensive, and occupies a significant topside area of the offshore production unit. In some cases, this area occupation can be as high as 60% [2], which can make the production from these reservoirs unfeasible.

To overcome these difficulties, new technologies are proposed, such as the high-pressure dense phase subsea separator (HISEP®) [2]. This technology allows for the subsea separation of at least two phases, a liquid rich in hydrocarbons and a dense, supercritical phase rich in CO_2 [2,3]. Then, the liquid phase is sent to the production unit, while a subsea multistage centrifugal pump could be used to inject the CO_2–rich dense phase into the reservoir.

Besides other mechanical aspects, it is not clear whether a typical centrifugal pump, which is usually designed to work with liquids, will work under similar performance when handling a supercritical fluid in comparison with its baseline operation with water. Regardless of their high density, supercritical fluids have greater compressibility than liquids [4]. Thus, the temperature increase of the fluid through the pump, which is usually not a concern for most liquid operations, with the exception of very viscous liquids, becomes important when it comes to pumping compressible fluids such as supercritical CO_2, because the compression work, the density variation, and the other thermophysical properties directly depend on this parameter.

In this context, the present work aims to evaluate the performance of a multistage centrifugal pump operating with supercritical CO_2, through a numerical approach using ANSYS® CFX® software. With the numerical results, we intend to explore the problem as a way of evaluating the feasibility of using a centrifugal pump for pumping supercritical fluid in terms of its performance.

Therefore, to obtain representative results of the problem, the real variation in the thermos-physical properties of the fluid is simulated through the implementation of thermodynamic tables in the numerical model, while the performance and temperature increase of the pump are evaluated through a polytropic approach, a borrowed concept of compressor theory.

In addition, an algebraic model to calculate the fluid temperature rise along the pump is also proposed in order to have an additional tool to help in the evaluation of supercritical fluid pumping performance.

Methodology

To model, the single-phase flow of a supercritical fluid within a rotating subdomain, the governing equations of the problem, continuity, momentum, and total energy transport equation, are numerically solved assuming Reynolds averaging for turbulence modeling (RANS) in a non-inertial reference system, through Element-based Finite Volume Method and the Frozen-Rotor as implemented in the ANSYS® CFX® computational fluid dynamics package (2022).

The flow turbulence was modeled using the $\kappa - \omega$ SST model [5]. This model adequately predicts turbulent flows in regions close to and away from walls. In addition, it is considered one of the most suitable for modeling turbomachinery operating with supercritical fluid [6,7].

The domain of the numerical solution is based on the 9-stage centrifugal pump model CM1-9 from Grundfos®. However, the numerical model assumes only three stages of the pump, since simulating all nine stages proved too computationally expensive.

As the stage's rotor and diffuser have both six blades, only 1/6 of the azimuth extent (360º/6=60º) of the geometry was modeled, saving computational time. At the inlet of the domain, suction pressure and temperature are specified, while the mass flow is specified at the outlet.

A mesh sensitivity test for the 3-stages of the simulated centrifugal pump was performed in terms of pressure increase and torque considering six levels of grid refinement, three operating conditions (0.5·BEP, BEP, and 1.5·BEP), and a rotating velocity of 3480-rpm. Fig. 1 shows the percentage deviation of the pressure rise and torque obtained with five different mesh grids for the three flow rate operations. Mesh number 6 is used as a reference and it has a total of 5,658,657 nodes.

It can be noted that Grid number 5 presented the overall least deviation in both pressure rise and torque for all flow rates considered. For example, the pressure rise and torque deviations at BEP flow rate were 0.25% and 0.07% respectively. The most significant deviation obtained with Grid 5 was 1.72% for pressure rise and 1.12% for torque, both for the 1.5BEP operating flow rate. For all these reasons, grid 5 was used in our numerical simulations.

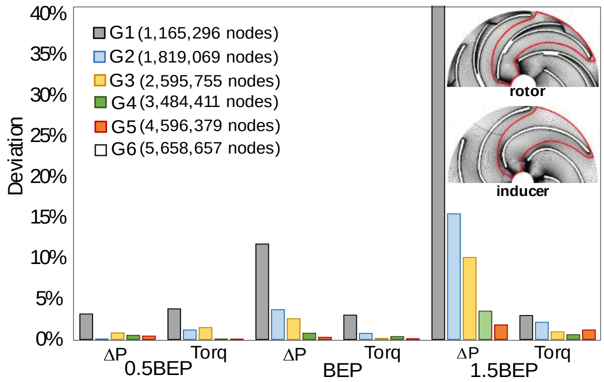

Figure 1. Deviation between pressure increment and torque results obtained using grids with different nodes number. The deviation is calculated with respect to G6.

Variations of the thermo-physical properties of supercritical CO_2 were simulated through interpolations on RGP (Real Gas Properties) thermodynamic table, which is previously calculated using models from the NIST® REFPROP® program and coupled to ANSYS® CFX®. This allows obtaining more stable numerical simulations with less computational time compared to solving an actual equation of state during run-time [7].

Results and Discussion

To verify the validity of the numerical model, the numerical results are first compared with experimental data from the pump operating with liquid water at 4500 rpm, as indicated in Fig. 2, which compares numerical and experimental data of pressure rise, power and efficiency as a function of flow rate. A good agreement between the two cases is observed.

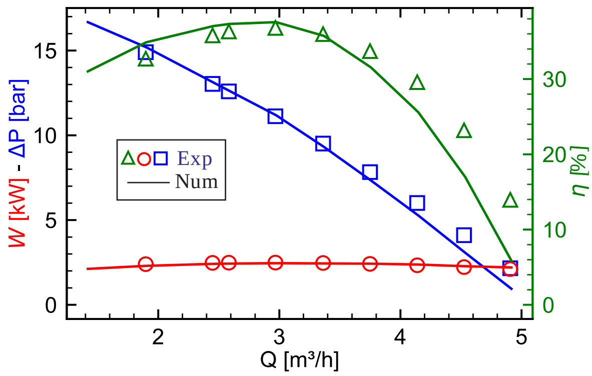

Figure 2. Comparison between numerical and experimental data of pressure, power and efficiency, as a function of flow rate, for the pump operating with water at 4500 rpm.

Although the numerical model slightly underestimates the experimental data at high flow rates, it agrees generally well with the experimental data through almost the whole operational curve of the pump, especially close to the best efficiency flow rate, 2.97 m³/h. In this sense, it is believed that the model is well-calibrated and can be used as a reference in the analysis of simulations with supercritical CO_2.

Figure 3 shows the curves of dimensionless head, ψ, and power coefficients, Π, as a function of the flow coefficient, ϕ, for simulations of the centrifugal pump operating with water (baseline) and supercritical CO_2 at different rotating speeds and thermodynamic suction conditions.

For both coefficients, ψ and Π, similar behavior is observed. Both performance curves for supercritical CO_2 present excellent agreement, which are also found to be close to the dimensionless water curve. This behavior suggests that the ordinary hydrodynamics similarity laws of pumps used with liquids can be extended for supercritical fluid.

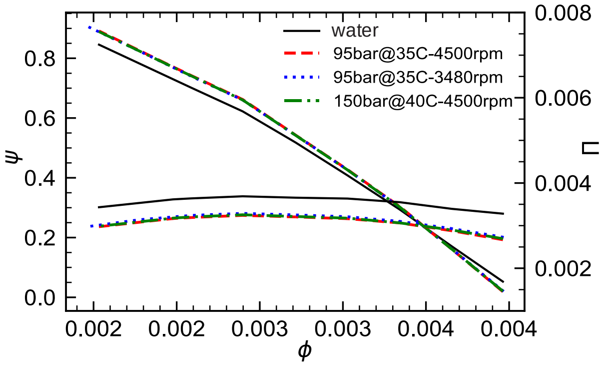

Figure 3. Head and power coefficients as a function of the flow coefficient for the centrifugal pump operating with supercritical CO_2 under different conditions and with water.

However, a small displacement of the CO_2 curves in relation to the water curve is observed. This may be a consequence of the lower viscosity of supercritical CO_2, so the head coefficient is slightly higher and the power consumption is lower, positively affecting the pump's efficiency.

Figure 4 shows the temperature increase curves obtained through the CFD model (baseline), the polytropic approach, Eq. (3), the first law of thermodynamics, Eq. (2) and our proposed model, Eq. (1), for 3-stage of the pump operating with supercritical CO_2 under two rotating speed and at a suction condition of 95 bar and 35 ºC.

$$\Delta T = \frac{\dot{W}_{eixo}}{\dot{m}.c_{p1}} + \bar{\mu}_{JT}(\Delta P)$$
$$\bar{\mu}_{JT} = \frac{\mu_{JT}(T_1,P_1) + \mu_{JT}(T_1,P_2)}{2} \quad (1)$$

$$h_2 = \frac{\dot{W}_{eixo}}{\dot{m}} + h_1 \Rightarrow T_2 \longrightarrow T(P_2,h_2) \quad (2)$$

$$T_2 = \left(\frac{P_2}{P_1}\right)^m \rightarrow m = \frac{P_1}{c_{p1}}\left[\frac{v_1}{T_1}\left(\frac{1}{\eta}-1\right)+\left(\frac{\partial v}{\partial T}\right)_P\right] \quad (3)$$

where *P, T, h, v*, c_p, μ_{JT} and $\dot{m}$ represent the pressure, temperature, enthalpy, specific volume, specific heat at constant pressure, Joule-Thomson coefficient and mass flow rate of the fluid, respectively; $\dot{W}$ and η are the pump's power consumption and efficiency. Subscripts 1 and 2 represent pump's suction and discharge conditions, respectively.

It is observed that the proposed model has the ability to predict the temperature increase with an accuracy similar to the one obtained with the other traditional models. In addition, all models show a good agreement with the temperature rise curve obtained numerically.

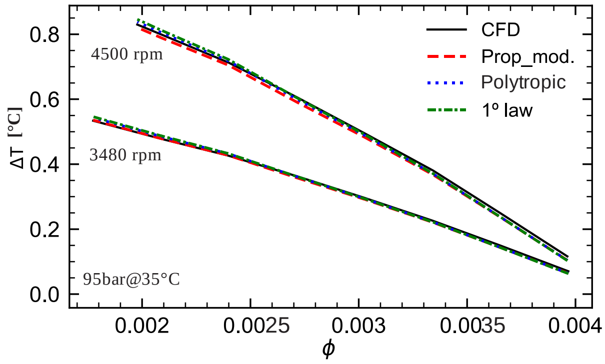

Figure 4. Temperature increase curves obtained through CFD, the proposed model and traditional models for the pump operating with supercritical CO_2 under different operation conditions.

The results also show the significant influence of the rotating speed on the fluid temperature rise. This behavior is expected since the consumed power and pressure rise of the centrifugal pump are proportional to its rotating speed. Then, as the proposed model, Eq. (1), indicates, the temperature increase is directly proportional to these two operational parameters, although the thermodynamic condition at the pump suction is also important in this respect. In addition, it can be seen that the higher the flow rate, the lower the temperature increase. Again, this behavior is related to the pressure increase of a centrifugal pump, which decreases as the flow rate increases. Although the results shown in Fig.4 are temperature increments in the range of one degree Celsius, it is essential to note that they are only for three of the nine pump stages. Therefore, as the number of stages increases, the pressure and temperature increase as well. On the other hand, if the centrifugal pump operates close to the critical point a minimal variation of 0.5ºC could abruptly change the fluid properties and mischaracterize the pump's behavior. Then, evaluating properly the fluid temperature could be very important to characterize pumping supercritical fluids.

Conclusions

This work investigates the performance of a multistage centrifugal pump operating with supercritical CO_2 through numerical simulation in ANSYS® CFX® software. Results from simulations show that the typical hydrodynamics similarity laws of pumps used with liquids can be used for work with a supercritical fluid. The results for temperature increase obtained with the proposed model showed satisfactory agreement with those from the CFD model and other traditional models. Outcomes from this investigation could help to bring further understanding of the behavior of centrifugal pumps working with supercritical CO_2.

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Responsibility Notice

The authors are the only ones responsible for the paper content.

The authors declare no competing financial interest.

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