Research Article / Mechanical Engineering, Mechatronics, and Materials Science https://doi.org/10.15446/ing.investig.93419

Effect of Temperature on a Vortex Reactor for Hydrodynamic Cavitation

Efecto de la temperatura en un reactor vórtice para cavitación hidrodinámica

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ABSTRACT

The oil and gas sector has recently shown an interest in hydrodynamic cavitation for oil enhancement, as it allows reducing transportation and refinement costs. This work presents a fluid-dynamic study of Colombian oil at different temperatures passing through a vortex reactor. First, an experimental design was elaborated, establishing the temperature and quantity of the injected hydrogen donor as factors and the final viscosity of oil as the response. Then, a numerical model was developed in the Ansys Fluent software using multiphase models, where the required properties of the fluid were obtained via laboratory tests and the Aspen HYSYS software. The results obtained from numerical experimentation were analyzed, and it was observed that the final viscosity was less affected by the temperature than by the hydrogen donor. Moreover, numerical modeling showed an exponential relation between vapor generation and temperature. The experimental and numerical data were compared, and it was found that the temperatures established in the experimental design were not high enough to generate a significant amount of vapor, which is why the decrease in viscosity was lower.

Keywords: computational fluid dynamics, hydrodynamic cavitation, heavy crude oil

RESUMEN

Últimamente, el sector de petróleo y gas ha mostrado interés en la cavitación hidrodinámica para la mejora del petróleo, ya que esta permite reducir los costos de transporte y refinamiento. Este trabajo presenta un estudio fluidodinámico de petróleo colombiano a diferentes temperaturas mientras pasa por un reactor vórtice. Primero se realizó un diseño experimental, estableciendo la temperatura y la cantidad de donante de hidrógeno inyectado como factores y la viscosidad final del aceite como respuesta. Luego se desarrolló un modelo numérico en el software Ansys Fluent utilizando modelos multifase, donde se obtuvieron las propiedades requeridas del fluido mediante pruebas de laboratorio y el software Aspen HYSYS. Se analizaron los resultados de la experimentación numérica y se observó que la viscosidad final se vio menos afectada por la temperatura que por el donante de hidrógeno. Asimismo, el modelado numérico mostró una relación exponencial entre la generación de vapor y la temperatura. Se compararon los datos experimentales y numéricos, y se encontró que las temperaturas establecidas en el diseño experimental no eran lo suficientemente altas para generar una cantidad significativa de vapor, por lo que la reducción de la viscosidad fue menor.

Palabras clave: mecánica de fluidos computacional, cavitación hidrodinámica, petróleo crudo pesado

Received: February 6th, 2021
Accepted: May 10th, 2022

Introduction

Cavitation is the physical phenomenon that occurs in a fluid when vapor cavities are formed due to a pressure drop, which can be generated by a sudden decrease in the flow cross-sectional area. When designing an experiment that involves cavitation, parameters such as velocity, temperature, and the geometry through which the fluid passes must be considered (Barona-Mejía *et al*., 2021; Šarc *et al*., 2017).

Mathematical models can simulate cavitation by describing the phase change and behavior of the bubble. One of the most commonly used models is the Singhal method, also known as the full cavitation model, since it describes the formation and transport of the bubble, the turbulent fluctuations, and the magnitude of non-condensable gases (Singhal *et al*., 2002). Another widely known model is the

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How to cite: González-Estrada, O. A., Rojas-Nova, M. A., and González-Silva, G. (2022). Effect of Temperature on a Vortex Reactor for Hydrodynamic Cavitation. *Ingeniería e Investigación, 42*(3), e93419. https://doi.org/10.15446/ing.investig.93419

Schnerr-Sauer method, which is a combination of the VOF (Volume of Fluid) technique and a prediction of bubble growth and collapse (Sauer and Schnerr, 2000).

One of the parameters that affects cavitation is temperature, which has been studied in different ways, be it to determine erosion in solids (Dular, 2015) or to study bubble dynamics (Petkovšek and Dular, 2013). Moreover, the thermal effect has been studied in hydrodynamic cavitation reactors used for water cleaning (Ge *et al.*, 2022; Sun *et al.*, 2018). Another parameter is the geometry through which the fluid passes, among which Venturi tubes are the most common (Shi *et al.*, 2019). Given its basic configuration, this geometry has been used to test different turbulence models (Nouri *et al.*, 2010) or to compare experimental and computational data (Cappa *et al.*, 2014).

Additionally, during the hydrodynamic cavitation process for oil upgrading, a hydrogen donor such as gasoline (Yang *et al.*, 2013) needs to be added in order to avoid the reorganization of the free radicals in heavier molecules during the implosion of bubbles, thus preventing the crude from becoming even more viscous (Askarian *et al.*, 2017).

The oil and gas sector has different applications for the use of cavitation within crude refining processes, *e.g.*, enhanced recovery, de-metallization, viscosity reduction, desulfurization, and upgrading (Avvaru *et al.*, 2018). In terms of upgrading, hydrodynamic and acoustic cavitation are the most attractive from an industrial point of view (Montes *et al.*, 2018; Olaya-Escobar *et al.*, 2020; Sawarkar, 2019). Consequently, projects have focused on making this process profitable. However, a number of design parameters must be considered, which means that further research is needed (Gogate and Pandit, 2000). In this sense, several works have shown that vortex reactors using hydrodynamic cavitation are more energy-efficient for oil upgrading in comparison with thermal cracking and acoustic cavitation (Quan *et al.*, 2011; Sawarkar, 2019; Senthil Kumar *et al.*, 2000).

The purpose of this study is to evaluate the effect of temperature on a vortex reactor for hydrodynamic cavitation. The fluid of study is heavy crude oil, and the evaluation is carried out experimentally and numerically by using Ansys Fluent.

Materials and methods

The methodology was divided into two parts: the first one consists of the experimentation process in the vortex reactor; and the second one is the computational fluid dynamics analysis performed in the Ansys Fluent software.

Experimental design

The effect of temperature was determined via a two-factor, three-level experimental design. The factors evaluated were the temperature and the percentage of injected hydrogen donor, and the response variable was the final viscosity when the crude had already undergone the hydrodynamic cavitation process. All tests were performed with a crude flow rate of 12 GPM.

The data employed are shown in Table. 1. The initial viscosity was measured before the oil was introduced into the vortex reactor. The initial viscosity was not measured in the presence of hydrogen. Overall, there was a decrease in viscosity as the temperature increased. However, it was much lower when compared to that generated by an increase in the percentage of the injected hydrogen donor. A statistical analysis was conducted in the Minitab software for a detailed assessment of the effect of each factor.

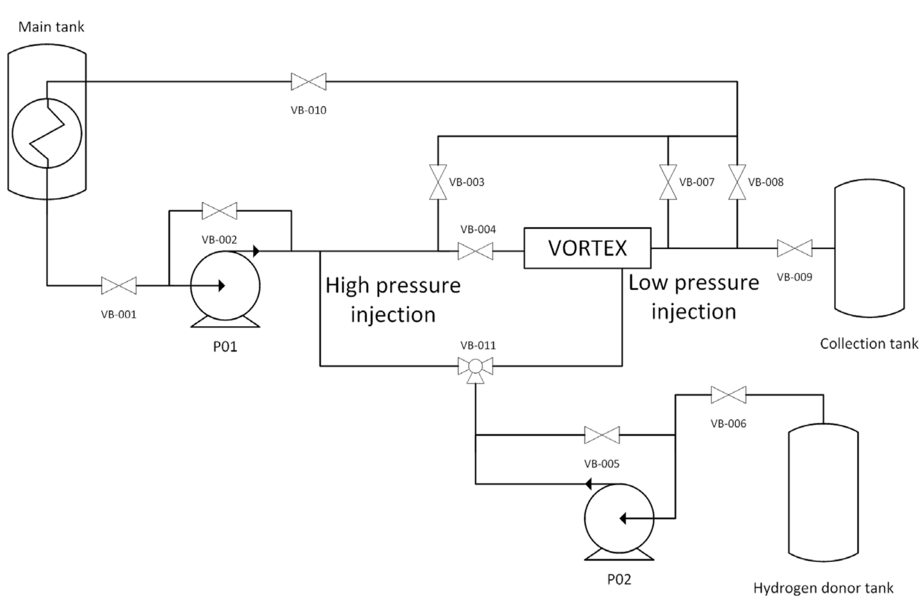

Figure 1. Diagram of the vortex reactor system
Source: Authors

The tests were run in the vortex reactor owned by the Energy Rap Vortex Services company (Quiroga *et al.*, 2021)**.** shows the complete system that made the reactor functional. It is composed of the pumping subsystem; the piping subsystem; the storage subsystem, which can elevate the oil temperature to 180 °F; the control subsystem; and the vortex reactor. The hydrogen donor can be injected into the oil with high or low pressure. In this case, the latter was employed. Note that the phenomena of mixing and vapor generation were not studied independently. It was assumed that these two conditions affect the performance of the vortex reactor (Quiroga *et al.*, 2021).

Table. 1 Results obtained from the experimental design

Iter	Hydrogen donor [%]	Temperature [°F]	Initial Viscosity [cP]	Final Viscosity [cP]	Viscosity reduction [%]
1	2	92	740	710	4,054
2	2	140	740	702	5,135
3	2	180	740	692	6,486
4	3	94	740	464	37,297
5	3	141	740	463	37,432
6	3	180	740	452	38,919
7	4	93	740	342	53,784
8	4	141	740	335	54,730
9	4	180	740	331	55,270

Source: Authors

Cavitation model

Modeling cavitation in the vortex reactor allowed studying the fluid-dynamic behavior of the oil. The parameter of interest in the numerical model was vapor generation, which is a consequence of the cavitation process.

The selection of numerical models was carried out by reviewing the works of several authors (Moll *et al.*, 2011, 2012; Salvador and Frankel, 2004; Darbandi and Sadeghi, 2009), who simulated the behavior of a cavitating fluid in injectors. This research is based on a widely recognized experimental study in this field (Nurick, 1976).

The turbulence model used was the K-Epsilon Realizable with Standard Wall Functions because the viscous effects near the wall were not relevant. As there is cavitation, there is a two-phase flow. For this reason, a mixture model was chosen in conjunction with the Schnerr-Sauer method in order to model the formation of bubbles. Since the behavior and evolution of bubbles is not a concern in this project, the model was run in a steady state.

The geometry used corresponds to the volume of fluid extracted from the vortex reactor, which is shown with the corresponding scale in Figure 2. The inlet and outlet domains for the boundary conditions are indicated in the isometric view in Figure 2a. Detailed geometric dimensions are not provided for patent protection purposes.

The values established as boundary conditions for each numerical model are shown in Figure 2a, where the first three were taken from the experimental stage. Furthermore, two models with pressure values corresponding to higher temperatures were added, which were obtained through a mathematical correlation. Finally, the walls were treated with the conditions of non-slip and zero flow.

Table 2. Boundary conditions for each numerical model

Model	Inlet pressure [psi]	Outlet pressure [psi]
1	360	14
2	335	14
3	325	14
4	308,6	14
5	293	14

Source: Authors

A mesh independence study was conducted in order to find the appropriate element size. Overall, five meshes were employed which had between 1 179 758 and 8 474 211 elements. Finally, a mesh with 6 764 078 first-order elements was selected. The skewness, orthogonal quality, and aspect ratio were evaluated, and they are shown in Table 3. Note that the quality of the mesh is enough to achieve a good accuracy and avoid high discretization errors.

Table 3. Quality parameters of the selected mesh

Parameter	Minimum value	Maximum value	Average value
Aspect ratio	1,002	29,267	2,661
Skewness	8,832E-9	0,799	0,166
Orthogonal quality	0,2	1	0,857

Source: Authors

The numerical results were evaluated using various guidelines related to the validation and verification of computational fluid dynamics simulations (Freitas, 2002). To define the models, prior characterization of the oil in the liquid and vapor phase was necessary. To find the required properties, the Aspen HYSYS software was used in conjunction with the data obtained from the following tests:

- ASTM D445 for viscosity (2021)
- ASTM D1298 for API gravity (2017)
- ASTM D86 for a distillation curve (2020)
- PVT analysis

Figure 3 shows the configuration used in Aspen HYSYS. It has an oil stream whose properties were obtained using the previous tests, a control valve to throttle the fluid and generate two phases, and a flash drum to independently obtain the properties of vapor and liquid.

Once the configuration was set, five different conditions were established on the crude stream, which are shown

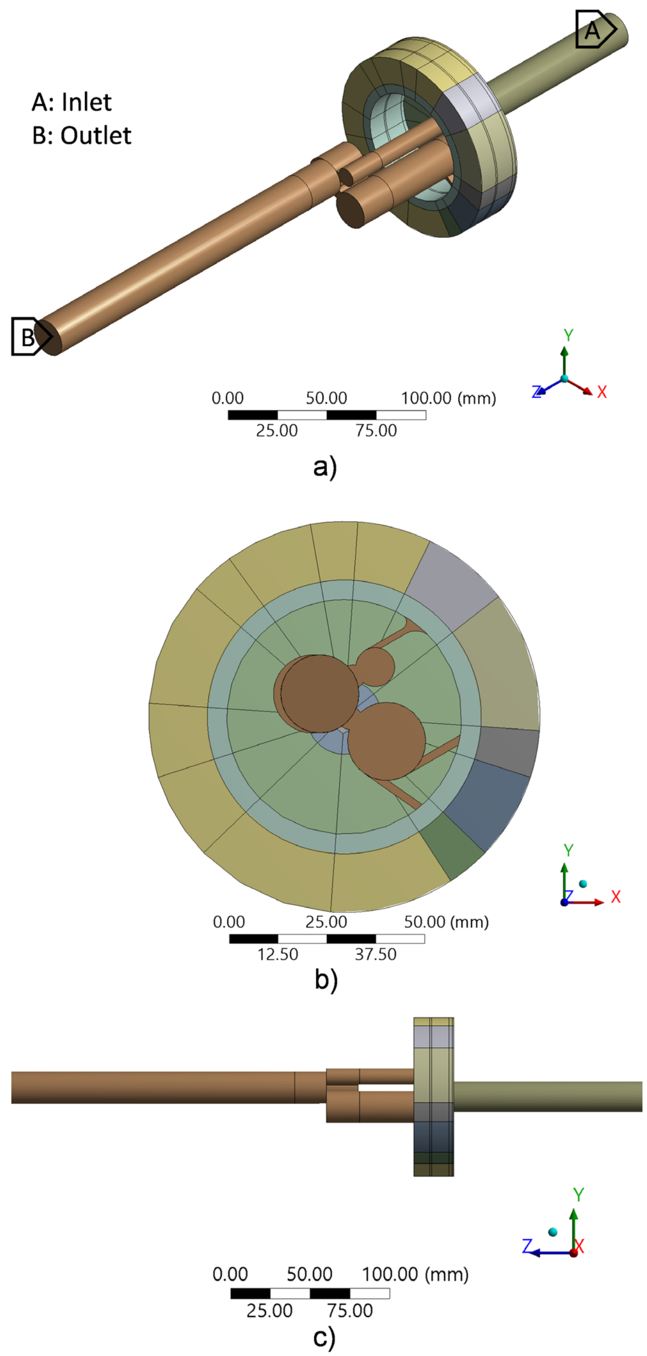

Figure 2. Volume of fluid extracted from the vortex reactor: a) isometric view with inlet and outlet domains, b) front view, c) side view
Source: Authors

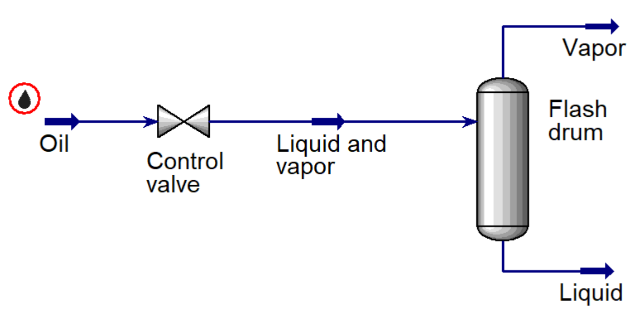

Figure 3. Aspen HYSYS configuration for oil characterization
Source: Authors

in Table 4. The first three conditions are the values used in the experimental stage, when a 2% hydrogen donor was injected. Additionally, two conditions were added, with higher temperatures to evaluate the behavior of the vapor fraction.

Table 4. Oil stream conditions used in Aspen HYSYS

Condition	Temperature [°F]	Pressure [psi]
1	92	360
2	140	335
3	180	325
4	250	308,6
5	350	293

Source: Authors

Results

Statistical analysis of experimental data

The data obtained through the experimental design was evaluated using Minitab. The individual effects of each variable on the final viscosity were entered, and a statistical analysis was performed.

The Pareto chart of standardized effects can be seen in Figure 4. When the bar of one of the factors crosses the dotted line with a value of 2,8, it can be considered to be statistically significant. In this case, both the temperature and the injected hydrogen donor crossed it. Nevertheless, the donor did it to a greater extent, which means that it has a greater effect on the final viscosity.

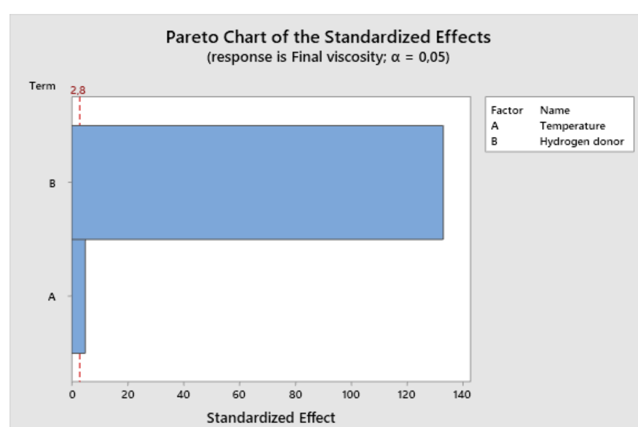

Figure 4. Pareto chart of standardized effects
Source: Authors

Moreover, the main effects of the levels of each factor on the viscosity can be seen in Figure 5. The temperature showed an almost horizontal line at the different levels, which means that its effect on the final viscosity is low. On the contrary, the hydrogen donor presented inclined lines at its different levels, which suggests that there is a considerable effect on the response variable.

Vapor generated from cavitation

The generated vapor was the variable of interest in the model because, with it, the effect of temperature on cavitation can be observed. Figure 6 shows the vapor fraction isosurfaces at the different analysis temperatures, except for 92 °F, since there was no vapor. Note that there is an increase in vapor generation as the temperature rises. In total, four different zones were found and marked with a number.

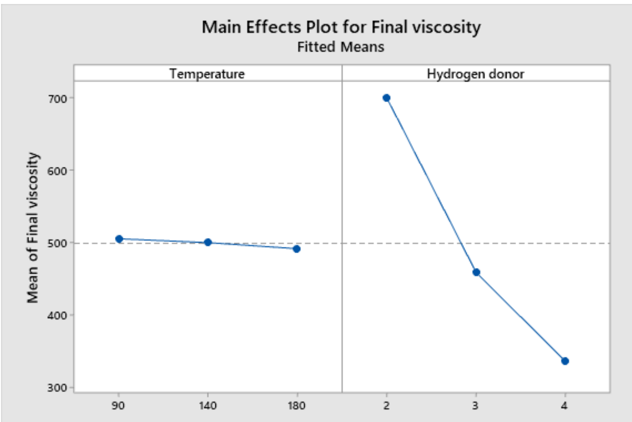

Figure 5. Main effects plot
Source: Authors

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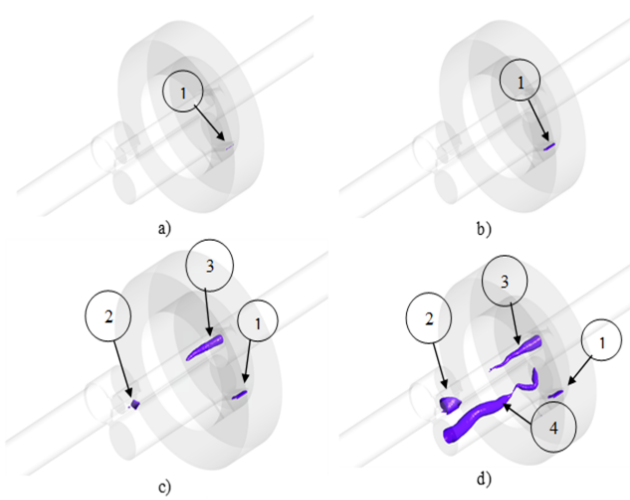

Figure 6. Vapor fraction isosurfaces at 140 °F (a), 180 °F (b), 250 °F (c), and 350 °F (d)
Source: Authors

Zone 1 occurs when there is a sudden reduction in the cross-sectional area and an abrupt change in the flow direction. This leads to a separation of the boundary layer from the walls and causes what is known as *vena contracta*, from which a recirculation zone is formed. Here, the static pressure can be lower than the vapor pressure, thus producing cavitation (Payri *et al.*, 2005). This phenomenon is usually studied in injector nozzles (Sou *et al.*, 2014). Likewise, in zone 2, a similar type of cavitation is generated since the flow is abruptly diverted.

Zones 3 and 4 correspond to cavitation generated by a vortex. Vapor is formed in its center, since there is a zone of low pressure because of the centrifugal force created by the rotation of the fluid. This phenomenon occurs mainly in the suction tubes of Francis turbines (Brennen, 1995).

The total vapor volume generated was obtained from the numerical models and was plotted as a function of temperature, as shown in Figure 6. At 92 °F, no vapor has yet formed, and, as the temperature rises, the amount of steam increases exponentially. The maximum value was 1,507 cm^3 at 350 °F. By contrasting the graph with the isosurfaces of Figure 7, the increase in vapor volume can be related to the aforementioned zones, thus implying that the vortices contribute the greatest amount.

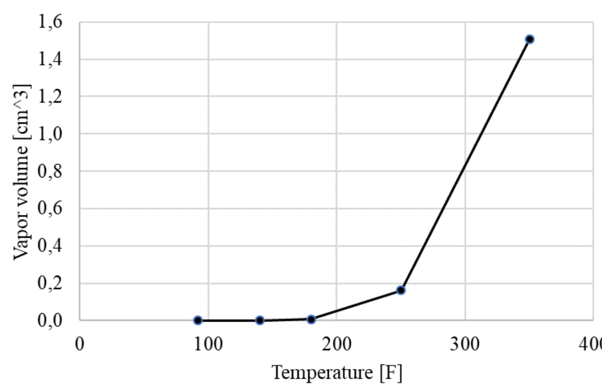

Figure 7. Variation of the vapor volume with temperature
Source: Authors

Conclusions

The experimentally obtained data showed that the increase in the fluid temperature during the tests did not have a considerable effect on the final viscosity of the oil. On the contrary, the increase of the injected hydrogen donor did achieve a high final reduction. This could be verified in the Pareto chart of standardized effects and the slopes of the main effects plot.

The Aspen HYSYS software, along with the ASTM D445, ASTM D1298, and ASTM D86 tests as well as the PVT analysis allowed completely characterizing the oil. The software proved to be a useful tool for obtaining the properties of the oil necessary to develop the numerical model in Fluent.

Using computational fluid dynamics, the behavior of the oil through the vortex reactor at different operating temperatures was modeled. It was found that, in the range from 92 to 180 °F, the vapor volume did not exceed 0,00685 cm^3. However, at 350 °F, the vapor volume increased significantly to 1,507 cm^3. By observing the isosurfaces, it was found that the sudden increase is due to cavitation in the vortices.

From the data obtained both experimentally and numerically, it is concluded that the temperatures employed in the tests were very low to have an effect on the final viscosity of the oil. Therefore, it is recommended to increase the power in the storage tank's resistance in order to reach higher temperatures. In addition, a feasibility analysis must be conducted since this change represents costs that could not be offset in the reduction of viscosity of the oil.

Acknowledgments

The authors would like to acknowledge the support given by Universidad Industrial de Santander (ERVS Agreement).

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Ingeniería e Investigación
vol. 42, no. 3, e212, 2022
Facultad de Ingeniería, Universidad Nacional de Colombia.,
ISSN: 0120-5609
ISSN-E: 2248-8723

DOI: https://doi.org/10.15446/ing.investig.93419