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Study of the effect of viscosity on the head and flow rate degradation in different multistage electric submersible pumps using dimensional analysis

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ABSTRACT

Multistage Electrical Submersible Pumps (ESPs) undergo performance degradation when operating with highly viscous fluids. Several studies on this subject seek to provide models to predict the pump performance under such conditions. However, some of those models require knowledge of geometric parameters or are only designated for radial-type pumps. In this article, dimensional analysis is used as an alternative to analyse head and flow rate degradation of different pumps without the need of any major geometric parameters. To accomplish this task, head curves for two multistage, mixed-flow type ESPs are obtained through a computational fluid dynamics (CFD) program for a wide range of viscosities and different rotational speeds. The numerical head curves were compared with experimental data under equivalent operating conditions and a good agreement was found. When adequate normalisations are used together with relevant dimensionless numbers, the head values obtained from the different ESPs proved to match quite well along curves of constant specific speeds. Experimental head values from literature for a radial-type centrifugal pump with volute operating with different fluid viscosities were used to extend the present analysis for a different pump geometry. Results from this procedure turned out to match the ESPs data well. A straightforward expression to correlate head and flow rate correction factors due to viscosity follows from the present approach, thus yielding a useful tool that might help in proposing a general method to estimate performance degradation.

1. Introduction

Electric Submersible Pump (ESP) systems are used to boost the production of oil wells. Those systems are composed mainly by an electric motor and a multistage centrifugal pump, and are currently used in both onshore and offshore applications. Especially in the latter case, costs of installation and maintenance are very high. Therefore, the proper function of the system operating at different flow rates and oil properties is highly desirable (Vieira et al., 2015).

Like almost any other pump, the hydraulic design of ESPs does not originally take the effect of the fluid viscosity on the flow pattern or pump performance into account. Indeed, the regular data sheets provided by ESP manufacturers are obtained from tests with water as the operating fluid. It is known, however, that pumps are subjected to performance degradation when operating with oils due to a significant increase in friction losses and changes in flow pattern caused by the high fluid viscosities involved. When compared to data obtained with water, head and efficiency are degraded and the best efficiency point (BEP) shifts to a lower flow rate as showed by Stepanoff (1967).

Experimental and mechanistic studies about the influence of viscosity on the performance of centrifugal pumps have been conducted over several years (Ippen, 1945), Stepanoff (1967), Pfleiderer and Petermann (1979), Sun and Prado (2006) and Gülich (2010)). Such studies brought a great deal of information about the many types of losses that occur inside the centrifugal pump and the influence of viscosity on its performance. Some of those studies also propose methods to predict the pump performance under highly viscous flows, but they are mostly validated for centrifugal pumps with radial-type impellers, which may not be applicable to mixed-flow type geometries, or the method needs several geometrical parameters that are hard to get.

Amaral (2007) and Amaral et al. (2009) studied the influence of viscosity in different centrifugal pumps, two ESPs and one with two radial impellers and a volute. The authors proposed a model to predict the performance degradation in a centrifugal pump using a mechanistic

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Nomenclature

b	blade height [m]
C_Q	flow rate correction factor [−]
C_Q	head correction factor [−]
D	diameter [m]
D_h	hydraulic diameter [m]
e	blade thickness [m]
g	gravitational acceleration [m/s^2]
H	head [m]
n	rotational speed [rpm]
n_q	specific speed (with rpm, m^3/s and m)
p_{ref}	reference pressure [Pa]
Δp	pressure gain [Pa]
∇p	pressure-gradient [Pa]
Q	volumetric flow rate [m^3/s]
$\vec{r}$	position vector [m]
Re_{D_H}	Reynolds number based on the hydraulic diameter at the intake pipe [−]
Re_Ω	rotational Reynolds number [−]
R^2	: coefficient of determination [−]
S	source term of the general transport equation of property ϕ [−]
$\vec{V}$	velocity vector [m/s]
$\overrightarrow{V_{xyz}}$	relative velocity vector [m/s]
V	mean velocity [m/s]
Z	number of blades/vanes [−]

Greek symbols

β	blade angle [deg]
ϕ	generic transport property [−]
Φ	flow coefficient [−]
Ψ	specific head [−]
γ	intermittency variable [−]
Γ	generic diffusion coefficient of the general transport equation of property ϕ [−]
η	hydraulic efficiency [%]
μ	dynamic viscosity [Pa·s]
μ_t	eddy viscosity [Pa·s]
ν	kinematic viscosity [m^2/s]
Re_θ	momentum thickness Reynolds number [−]
ρ	density [kg/m^3]
ω_s	specific speed [−]
Ω	impeller angular speed [rad/s]

Subscripts

1	impeller inlet
2	impeller outlet
3	diffuser inlet
4	diffuser outlet
des	design
i	inner diameter
o	outer diameter
n	normalised
w	value tested for water

approach which consisted of adjusting the Euler head curve using loss terms. To validate the proposed model they tested three centrifugal pumps operating with an aqueous solution of glycerol for different temperatures and glycerol concentrations. The model fitted the data rather well, but it may not be applicable for different geometries than the tested ones. Vieira et al., (2015) studied the effect of viscosity in a single stage of an ESP. They proposed a model to correct the effect of viscosity combining different definitions of losses from different authors. The authors compared the results with experimental data and a good agreement was observed. However, different combinations were used to represent different cases. There was not a unique combination capable of modelling the effect of viscosity in the ESP. Using a commercial CFD software, Stel et al. (2015) developed a numerical model to simulate the flow in three stages of an ESP. They evaluated the influence of the number of stages considered in the simulation, as well as the influence of turbulence models on the results. In addition, the authors evaluated the performance of the ESP operating with water for different flow rates, but no analysis of the influence of viscosity on the results was presented.

Performance degradation is generally related to viscosity, geometry of the centrifugal pump, rotational speed and flow rate. However, some works such as Solano (2009), Stel et al. (2014) and Paternost et al. (2015) suggested that dimensional analysis can be successfully used as a method to analyse performance curves for a given pump operating with fluids within a range of viscosities. Particularly, Solano (2009) verified that the performance of a given pump is degraded along a curve of constant specific speed. This property was proposed by Stepanoff (1967) for operation at the best efficiency point, but Solano (2009) confirmed that it also holds for off-design conditions, as long as proper dimensionless numbers definitions are used. Nevertheless, this study was conducted for a single pump only. Thus, the procedure adopted by the author may not be directly used to correlate performance data from different pumps. Using the same approach but other centrifugal pump, Paternost et al. (2015) also confirmed that performance degradation due to fluid viscosity occurs for constant specific speed. The authors extended their study considering two-phase flow at the inlet of the centrifugal pump. They observed that performance degradation for two-phase flow also occurs at constant specific speed, although for gas volume fraction up to 1% at the pump inlet.

Recently, numerical studies have been conducted to evaluate the performance of centrifugal pumps. The versatility of such approach is the main reason to use it. Shojaeefard et al. (2013) investigated the performance degradation caused in the pump when operating with oil using both experimental and numerical approach. Based on experimental and numerical results, the authors could propose an improved impeller geometry that handled oil better than the original. Also using numerical approach, Zhu et al. (2016) presented a numerical simulation of seven stages of an ESP. The authors observed a pressure peak in the diffuser, which consists of an interaction between impeller and diffuser. Ofuchi et al. (2017) conducted a numerical study about the effect of viscosity on a three stage ESP. The authors analysed the difference of the flow field inside the ESP channels increasing the fluid viscosity. They have shown that increasing the fluid viscosity changes the flow pattern inside the ESP. Recirculation and turbulence diminish and for very high fluid viscosity the flow is very well oriented.

Following the context exposed above, this work aims at investigating the performance degradation of two ESPs operating with viscous fluids by means of a dimensional analysis. The study focus on head evaluation, which is numerically calculated by using a commercial computational fluid dynamics software for a wide range of fluid viscosities and rotational speeds. Experimental data for a radial-type pump is later added to verify if the analysis can be extended to different centrifugal pump geometries. Two approaches to investigate head and flow rate degradation are presented. The first considers constant rotational Reynolds numbers, whilst the second assumes constant specific speeds. The main motivation is to obtain relevant dimensionless numbers that might be used to compare the head from different pumps without relying on geometric parameters.