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Original Article

Investigating the Critical Velocity of Cement Slurry with Contamination and Applying the Results to Improve Primary Cementing Job Design

William Ejuvweyerome Odiete

[1]*Department of Petroleum Engineering, Delta State University, Abraka, Delta State, Nigeria.*

Corresponding Author : williamodiete@gmail.com

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Abstract *- Investigating the critical velocity of cement slurry with contamination, gives an insight as to the changes to expect down-hole when cement slurry is contaminated with mud. It enables the engineer to know whether the cement slurry will still be in its design flow regime when contaminated. By comparing the annular velocity of the cement slurry with its critical velocity at any particular displacement rate during the design stage, it can be determined whether the annular velocity of the cement slurry will exceed its critical velocity for turbulent flow placement, especially when contaminated with mud. Thus enabling cementing engineers to proactively determine whether displacing the cement slurry in turbulent flow is achievable or not achievable during primary cementing. It also aids the engineer in deciding to pump enough pre-flushes in the turbulent flow ahead of the cement slurry. Results revealed that the critical velocity of the cement slurry increased with contamination at any particular temperature, as evidenced by the critical velocity of the contaminated cement slurries. Results showed that the mathematical models generated for the contaminated cement slurries could be used to predict the variation of the critical velocity of contaminated cement slurries with temperature, as evidenced by the high values of the regression coefficient, R^2 obtained.*
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Keywords *- Primary cementing, Flow regime, Cementing job design, Cementing job execution, Cement slurry contamination.*

1. Introduction

It is uncommon to displace a cement slurry in turbulent flow during primary cementing because of restrictions imposed by the rheology of the cement slurry, fracture gradient of the formation, open-hole size, annular clearance, placement pressures (including friction pressures) and pump capacity.

When displacement of cement slurry in turbulent flow is not possible, it is always advisable to place more emphasis on displacing the pre-flushes in turbulent flow instead of the cement slurry. Soares et al (2017) stated that well cementing has an enormous impact on the productive life of oil and gas wells, with the cement slurry providing hydraulic seal stability and also protecting the casing from correction.

Most times, when cementing job designs are done, the critical velocity of the cement slurry is calculated alongside the critical velocities of other fluids. The aforementioned implies that more emphasis should be placed on the critical velocity of the pre-flushes (spacers and chemical washes) than on the critical velocity of the cement slurry. When less emphasis is placed on displacing cement slurry in turbulent flow, fewer amounts of dispersants will be used in the design of cement slurries to the extent that the amount used would be enough to have a pumpable cement slurry and require fluid loss control. Therefore, for every primary cementing job, computer-aided simulation must also be done at the design stage to check if the formation can withstand the placement pressures to avoid fracturing the formation and the associated lost circulation. Pegasus Vertex Inc. (2024) stated that the design and planning phase of a cementing job is a critical phase for preventing common cementing problems.

Contamination of cement slurry with oil-based mud alters the properties of the cement slurry (Li et al 2016). To avoid contact between cement slurry and drilling mud, intermediate fluids called spacers and chemical washes are pumped ahead of the cement slurry (Soares et al. 2024).

The aforesaid implies that, there will be changes in the critical velocity of the cement slurry and the primary rheological properties when the cement slurry is contaminated with mud. Therefore, we must also prevent the cement slurry from being contaminated with the drilling mud.

In view of the aforementioned, this work investigated the variation of the critical velocity of cement slurry when contaminated with oil-based mud to give an insight into what to expect down-hole if cement slurry contamination with mud occurs during primary cementing. Such insight can prompt cementing engineers to assume at least 10% contamination at the design stage to simulate changes in the critical velocity of the cement slurry and quickly decide that displacement of the cement slurry in turbulent flow is achievable or not achievable and focus on pumping enough spacers and chemical washes in turbulent flow ahead of the cement slurry.

Wang et al. (2023) stated that cement slurry contamination with mud results in micro-cracks and pores on the cement/formation interface and a decline in the tensile strength of the cement sheath. Santos et al. (2019) reported that contamination of cement slurry with mud causes poor cement bonding to the formation and the casing in the wellbore.

The critical velocity of a flowing fluid is the velocity corresponding to the critical Reynolds number. Boyun Guo (2021) stated that the critical Reynolds number is the limit at which the flow of fluid changes from laminar flow to turbulent flow and that if the calculated Reynolds number is higher than the critical Reynolds number, the flow is turbulent, but if less than the critical Reynolds number, the flow is laminar.

Wikimedia (2024) wrote that the Reynolds number helps to predict fluid flow behavior by measuring the ratio between inertia and viscous forces and that at a low Reynolds number, flow is dominantly laminar, while at a high Reynolds number, flow is dominantly turbulent. Modeling the critical velocity of cement slurry with contamination will help the cementing engineer to predict the critical velocity of the contaminated cement slurry at other temperatures, especially in cases of emergency and when laboratory services are not immediately available.

2. Materials and Methods

Methods applied include laboratory testing and mathematical modeling using Microsoft Excel. The materials used are Class G cement, freshwater, antifoam additive and oil-based mud. The cement slurry was prepared according to API Spec 10B, while a mud company supplied the oil-based mud. The cement slurry and the mud were separately conditioned for 20 minutes in an atmospheric consistometer that was preheated to a test temperature of 27ºC, and rheology was separately conducted on each fluid using Chan-35 Rheometer. Fresh cement slurry was prepared, and the same procedure was repeated to measure the rheology of the cement slurry at the other test temperatures of 38ºC, 49ºC, 60ºC and 71ºC. After that, fresh cement slurry and oil-based mud were separately conditioned at each test temperature and mixed at the ratio of 90/10, 80/20, 70/30, 60/40, and 50/50 percentage by volume and the rheology conducted for each mixture at each test temperature using the Chan-35 Rheometer.

Wikimedia (2023) stated that, for flow through a pipe, the Reynolds number is given by

$$Re = \frac{\rho v D}{\mu}$$

Where, D = internal diameter of pipe, ρ = density of fluid, μ = viscosity of fluid, Re = Reynolds number, v = velocity of fluid

The critical velocity is the velocity corresponding to the critical Reynolds number. The critical velocity was calculated for the cement slurry and each of the contaminated cement slurry mixtures using a critical Reynolds number of 3000.

The internal diameter of the pipe was assumed to be 0.157m. The critical velocities of the cement slurry and the contaminated cement slurries were calculated using a cementing computer-aided design and evaluation software and plotted as presented in Figures 1 to 6.

$$v_c = \frac{Re_c \mu}{\rho D}$$

Where, D = internal diameter of pipe, ρ = density of fluid, μ = viscosity of fluid, Re_c = critical Reynolds number v_c = critical velocity

Microsoft Excel was used to generate mathematical models for the variation of critical velocity of cement slurry with temperature (Figure 1) and contamination with oil-based mud, as shown in Figures 2 to 6.

3. Results and Discussion

Results showed that the critical velocity of cement slurry increased with the rise in temperature, as evidenced by Figure 1. This is supportive of the fact that the plastic viscosity and yield stress of cement slurry increase with temperature.

Previous Study of Odiete (2023) reported that the plastic viscosity and yield stress of cement slurry increase with temperature. Odiete and Iyagba (2015) stated that the critical velocity of cement slurry increases with temperature.

The changes in the critical velocity of the cement slurry when contaminated with oil-based mud are represented in Figures 2 to 6. Nachiket and Teodoriu (2020) stated that contamination of cement slurry with oil-based mud changes its rheological and mechanical properties.

It is evident from Figures 2 to 6 that the critical velocity of the cement slurry increased with contamination at any particular temperature, as evidenced by the fact that the critical velocity of the contaminated cement slurry (Figures 2 to 6) at any particular temperature is higher than the corresponding critical velocity of the cement slurry (Figure 1) at that same temperature.

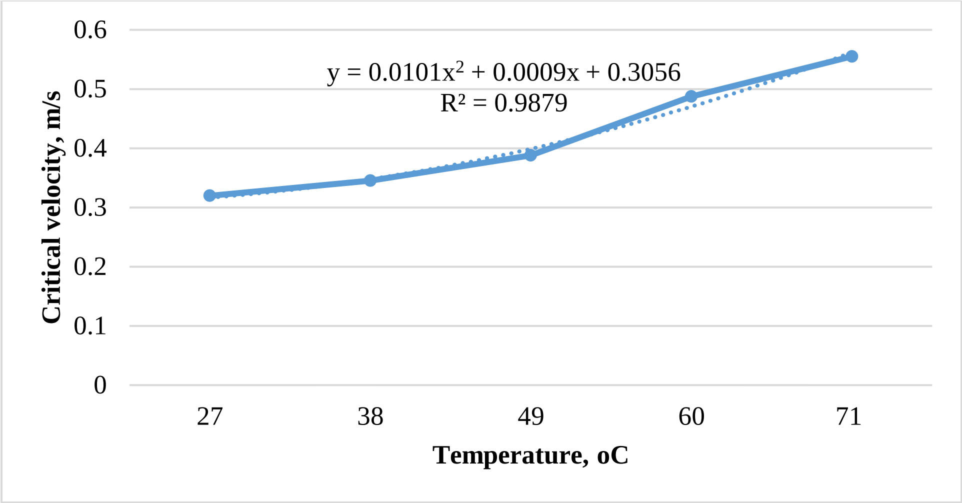

Fig. 1 Variation of the critical velocity of cement slurry with temperature

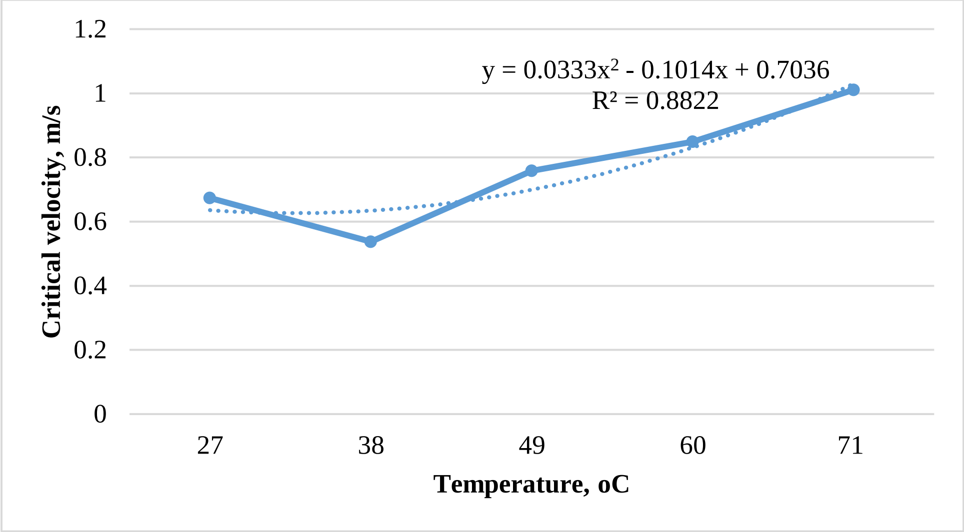

Fig. 2 Variation of the critical velocity of contaminated cement slurry (10% oil-based mud)

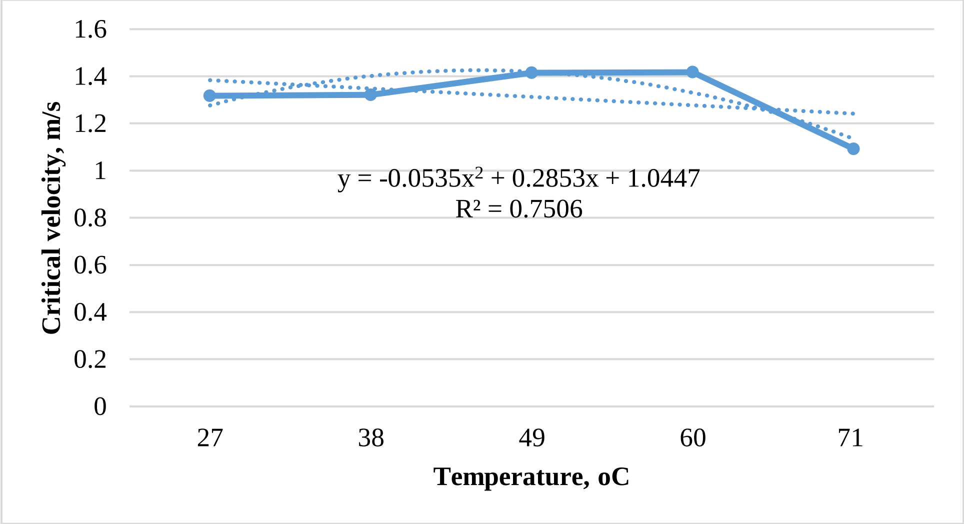

Fig. 3 Variation of the critical velocity of contaminated cement slurry (20% oil-based mud)

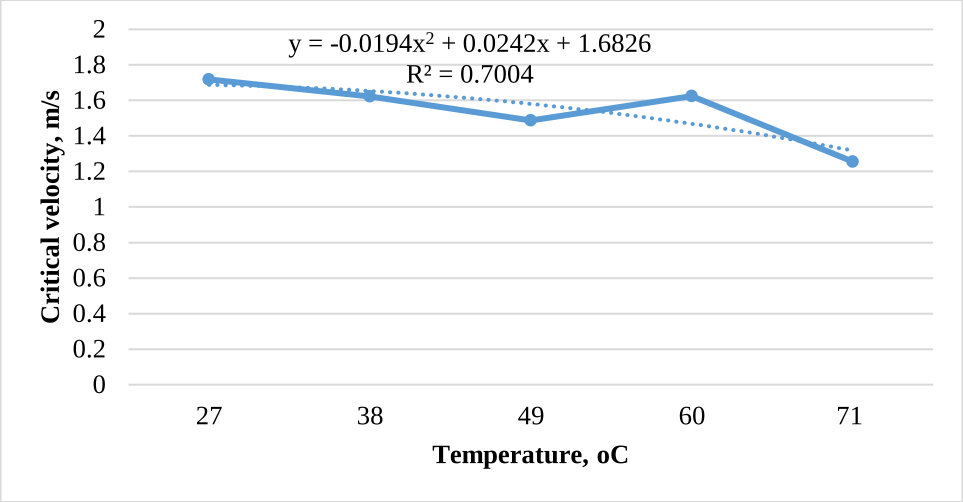

Fig. 4 Variation of the critical velocity of contaminated cement slurry (30% oil-based mud)

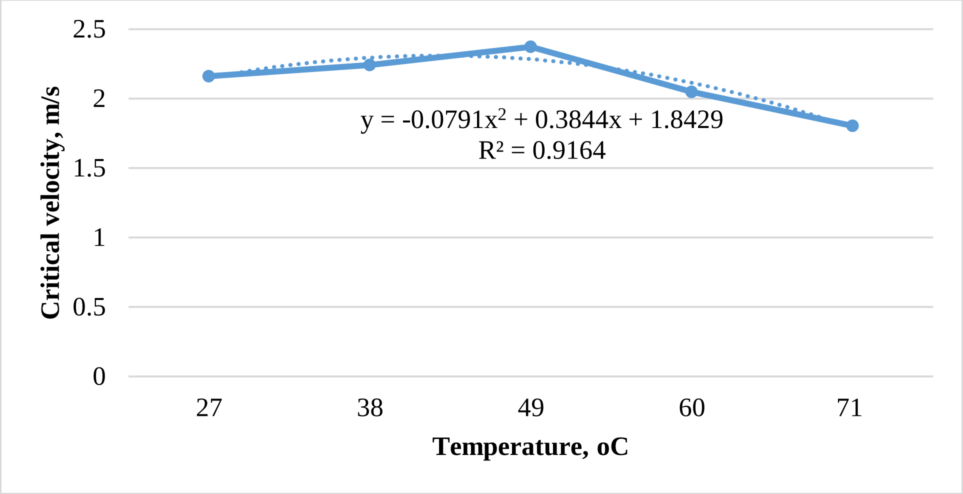

Fig. 5 Variation of the critical velocity of contaminated cement slurry (40% oil-based mud)

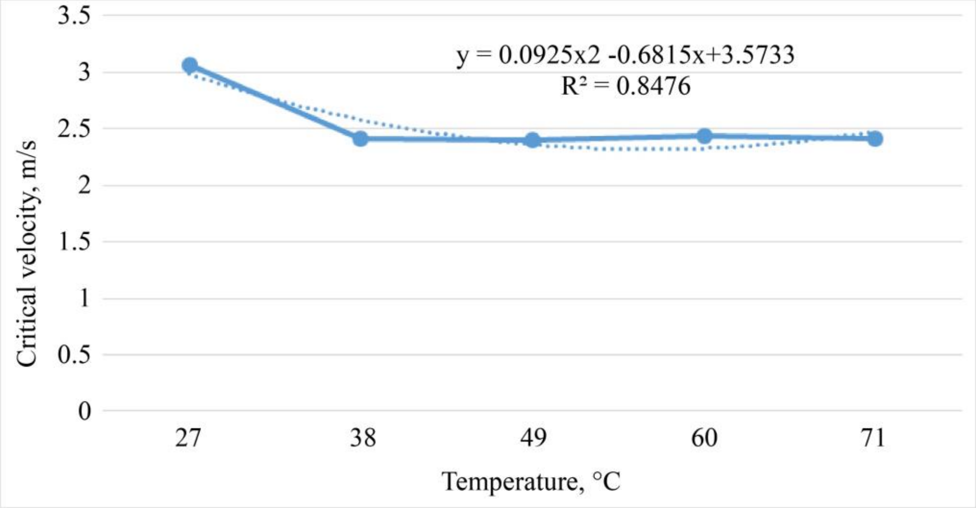

Fig. 6 Variation of the critical velocity of contaminated cement slurry (50% oil-based mud)

Therefore, to determine if cement slurry can be pumped in turbulent flow during primary cementing job design using a cementing job design and evaluation software, the following example would suffice for the primary cementing of a casing:

Part A

i) After pumping pre-flushes (chemical washes and spacers) and dropping the bottom plug.
ii) Pump cement slurry and drop top plug.
iii) Pump displacement mud at “y” m^3/min to displace the cement slurry into the annulus.
iv) Check the annular velocity of the cement slurry and compare it with the critical velocity of the cement slurry.
v) If the angular velocity of the cement slurry is higher than its critical velocity, the cement slurry is in turbulent flow; if otherwise, the cement slurry is in laminar flow.
vi) Check the placement pressure plot or the dynamic pressure plot to know if the fracturing of the formation occurred.
vii) If there is fracturing of the formation, go back to step (iii) and reduce the displacement rate until there is no fracturing of the formation.
viii) If fracturing occurs at every displacement rate, then the choice left is to ensure pumping enough pre-flushes (spacers and chemical washes) in the turbulent flow ahead of the cement slurry.

Part B (Simulating effect of contamination)

ix) Repeat step (iv) by comparing the annular velocity of the cement slurry with the critical velocity of the 10% contaminated cement slurry.
x) Check the annular velocity of the cement slurry and compare it with the critical velocity of the 10% contaminated cement slurry.
xi) Repeat steps (v) to (viii)

It is also evident from Figures 2 to 6 that the critical velocity of the contaminated cement slurry increased with contamination at any particular temperature. It can be seen that the critical velocity of the 20% contaminated cement slurry is higher than that of the 10% contaminated cement slurry at any particular temperature. Similarly, the critical velocity of the 30% contaminated cement slurry is higher than that of the 20% contaminated cement slurry. In comparison, the critical velocity of the 40% contaminated cement slurry is higher than the critical velocity of the 30% contaminated cement slurry at any particular temperature. The critical velocity of the 50% contaminated cement slurry is higher than the critical velocity of the 40% contaminated cement slurry at any particular temperature.

The aforesaid implies that when simulation of the critical velocity of cement slurry is done with contamination at the design stage, it will be detected early enough that the cement slurry can be pumped in turbulent flow (preferred) or laminar flow when contamination occurs down-hole during primary cementing. Limitations encountered in this work are funding and equipment.

4. Conclusion

The significance of this work to the oil and gas industry cannot be over-emphasized. The critical velocity of cement slurry increases with contamination at any particular temperature.

The very high regression coefficient obtained with the mathematical models for predicting the critical velocity of the contaminated cement slurries establishes that the corresponding mathematical models can be confidently applied to predict the effect of contamination on the critical velocity of a cement slurry during primary cementing and remedial cementing, especially in emergency situations where Laboratory services are not immediately available.

Modelling the critical velocity of contaminated cement slurry with temperature and extent of contamination will enable easier and better cementing job designs and the investigation of cementing job failures in the oil and gas industry.

Therefore, it is hereby recommended that mathematical models should be proactively developed to predict the critical velocity of the contaminated cement slurry at different temperatures and the percentage of contamination during the job design stage, especially for the primary cementing of production casings and liners.

The application of the mathematical models will provide a better understanding of cement slurry contamination with drilling mud and enable design engineers to proactively recommend the pumping of adequate spacer and chemical washes ahead of cement slurry during primary cementing and remedial cementing jobs to avoid cementing job failures.

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