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A Comprehensive Review and Background on Centrifugal Pump Performance under Multiphase Flow and Varying Operating Conditions

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Abstract: Centrifugal pumps play a critical role in various engineering sectors, particularly in applications involving the transportation of slurries mixtures of liquids and solid particles. Among these, slurry pumps are essential for industries such as phosphate mining and long-distance pipeline transport, where the efficient movement of abrasive and heterogeneous materials is vital. This review provides a comprehensive background on the performance of centrifugal pumps operating under multiphase flow conditions, with an emphasis on slurry handling. The interaction between pump performance and key parameters such as solid particle size, concentration, and density is examined, highlighting how these variables influence head loss, efficiency, and wear characteristics. While centrifugal pumps are widely utilized due to their cost-effectiveness and ability to manage high-throughput flow, their performance under challenging conditions—such as those involving cavitation—remains a subject of ongoing investigation. Cavitation, induced by localized pressure drops within the pump, can lead to vapor bubble formation and subsequent collapse, causing significant damage to internal components. The presence of solid particles adds complexity to this phenomenon, and the current understanding of how slurry affects cavitation behavior and long-term pump performance is still evolving. This review aims to synthesize existing research findings, identify critical knowledge gaps, and suggest directions for future studies to support the development of more robust and efficient centrifugal pump designs for multiphase flow environments.

Keywords: Slurry pumps, Two phases' pumps, Performance curves and non-cavitation

1. INTRODUCTION

This review is simply meant to serve as a general overview, and the thesis makes several references to further papers, such as those published on studies of the performance of centrifugal slurry pumps. These pumps have been created by appropriately altering the design of traditional centrifugal pumps to guarantee proper flow of solid-liquid mixture and to reduce erosive wear.

Because sand and clay are transported through pipes during mining and dredging activities, the pipe line system curve typically rises gradually as flow rate values increase. The flat pump head curve, which results in a substantial drop-in flow rate with a little change in head, makes choosing the operating domain challenging. As a result, changes in flow rate might result from a pump head curve drop of just a few percent. For the short- and medium-distance pipeline transportation of homogeneous and heterogeneous mixtures of solid materials, centrifugal slurry pumps are widely utilized. The reliability of the transportation system is significantly influenced by the features of the pumps. Due to the presence of solids, it is important to change clear water pump performance characteristics in order to achieve slurry centrifugal pump performance characteristics. Testing the pumps under various operating situations is also impractical, if not impossible. Coal, dirt, and gravel are among the course- and fine-grained materials that are hydraulically transported using centrifugal pumps with enshrouded and unshrouded impellers. The benefits of centrifugal pumps are based on a number of factors, including their high and reliable flow rate, easy and efficient controllability, favorable flow rate to model ratio, and inexpensive manufacture and maintenance costs. The head's small size and its poor efficiency are its main drawbacks. Additionally, over the course of the working life, efficiency degrades due to the wear of the impellers and the solids on the casing. Pump performance is impacted by the size of the pump, the solids density, the size and concentration of the slurry, and more. There are various ways to measure their impact. However, there are some elements that affect performance in situations with limited or no information, such as pump design and operation at high concentrations.

2. SOLID CONCENTRATION EFFECT

Slurries are being transported through pipe lines with an increasing number of centrifugal pumps. Understanding how solid concentration affects centrifugal slurry pumps' performance is crucial for designing a slurry handling system. When treating fine homogeneous type non-Newtonian slurries (coal/water and Kaolin/water), Walker and Goulas [1] used two different slurry pumps to study how the performance characteristics of centrifugal pumps changed. They concluded that the Reynolds number may be used to correlate the relative decrease in pump efficiency and head. The findings demonstrate that the rheological characteristics of the slurry affect the pump performance, with the Reynolds number of the pump generally providing a good correlation with the change in performance. Loss analysis was used by Roco et al. [2] to calculate the head-capacity parameters of centrifugal pumps that handle slurries. Local, secondary flow and friction were their three main divisions of the head losses. In addition, they created correlations to forecast different head losses for clear liquid losses and non-dimensional parameters defined by the characteristics of the slurry and the speed of the pump. They made precise predictions for handling silica sand up to 35% solids by volume concentration. Wilson [3] provided useful techniques for forecasting centrifugal slurry pump performance with extremely fine and coarse particles size, solids concentration, and density. He concluded that pump speed and flow rate had no effect on the proportionate losses in pump efficiency and head when pumping slurries. By employing two mine tailings with concentrations up to 60% by weight in a series of studies, Sellgren and Vappling [4] demonstrated that the drop-in head was restricted to around 15% and that, for concentrations over 40% by weight, the fall in efficiency outweighed the reduction in head. Additionally, when pumping highly concentrated slurries, they showed that the impacts of solids generally cannot be regarded as independent of the operating domain, i.e., pump speed and flow rate. The educational effects were greater with high concentrations of the finest tailing's product (maximum particle size equals 0.1mm), and a similar pattern was observed with a different pump and a coarser mineral. The decrease in efficiency was reasonably, well correlated to the pump Reynolds- number and the specific speed. Even while the effects of schooling are marginally more obvious in large pumps, the precise scaling conditions are not yet determined. The impact of solids on the effectiveness and head of centrifugal slurry pumps was researched by Sellgren et al. [4], and they concluded that the impact is less on larger pumps than on smaller ones. For gravel and sand products, the drop-in head was typically 3–10% when pumped at a concentration by weight of 30–35% in pumps with impeller vane widths of (0.12-0.23m) and impeller diameters of (1.1–1.2m). Up to values of 45–50%, the solid concentration by weight (Cw) could be linearly connected to the head drop. The particle size distributions were rather narrow, and the solid's specific gravity was approximately 2.66. Additionally, it was shown that for slurries with a foreign particle size distribution, the head reduction could be significantly smaller, negating the usefulness of using d50 (mass median particle diameter) as a representative particle size. For the data under investigation, the decline in clear water pump efficiency was equal to or less than the head decrease. They have tried to link experimental data for various pumps that are available in the literature with their own experimental data that includes weighted mean particle size of the solid material, normalized impeller diameter and width, and weighted mean particle size of the solid material. The book by Wilson, et al. [5] also provides a critical analysis of the impact of solids on pump performance. They have created generalized diagrams to estimate how well a pump will handle slurries. According to Kazim, et al. [6], the head reduction factor rises linearly as the solid's concentration rises. The weighted mean diameter seems to be a good choice to describe solid particle sizes that are not uniform. For slurries of all the materials investigated in the current inquiry and those that are referenced in the literature, the difference between the anticipated and the experimental head reduction factor is within ±10%. Pumps with different-sized metal and rubber-lined impellers were discovered to be compatible with their correlation. As a result, the correlation implicitly considers in a special way the impacts of the pump geometry, the shape factor of the solid particles, as well as the effects of the Reynolds number of the particles. They concluded that the current correlation is predicted to predict centrifugal slurry pump performance more accurately than the existing correlations. Focusing on the pumping of highly concentrated slurries, Ni et al. [7] found that the high solids concentration has a significant impact on pump head, efficiency, and power consumption, and that this impact differs depending on the size of the sand. When delivered at volumetric concentration (Cvd=42%), the pump efficiency in the coarse and slurry service may decrease by over 60% compared to that of the pure water service. They discovered that there is a critical volumetric concentration for the medium sand slurry of around 35%, at which both relative losses in pump head and efficiency declined more quickly. Efficiency ratio equals head ratio for fine and medium sands (ER=HR). Therefore, the power ratio of one (PR=1) is valid for concentrations of at least 35%. However, for coarse sand, when supplied volumetric concentration is larger than 15% (Cvd=15%), the pump efficiency decreases considerably more quickly than the pump head. Due to the spinning of the pump impeller, there may be two layers with differing solid concentrations in each route. Gandhi, et al. [8] created a method based on a loss analysis process to forecast how well centrifugal pumps will function when treating slurries. Their research considers the slurry pump's different construction from liquid pumps. Despite the fact that this methodology provides accurate forecasts (within a ± 12% error zone), it is requiring precise and thorough information about pump shape. In terms of the pump performance parameters, Gandhi, et al. [9] examined the performance of two centrifugal slurry pumps for three different solid materials (fly ash, zinc tailing, and bed ash) with varying particle size distributions. According to their findings, the head and efficiency ratio values are influenced by the particle size distribution of the solids as well as the slurry's characteristics, in addition to being dependent on solid concentration. They demonstrated that the decrease in head was 2-10% greater than the decrease in efficiency. The rise in pump input power might be interpreted as proportionate to the slurry's specific gravity for concentrations less than 30% by weight, they also noticed. Accordingly, it may be assumed that for the specified range of solids concentration, the proportionate losses in pump head and efficiency are the same.

3. PARTICLE SIZE EFFECT

A centrifugal pumps efficiency and clear water head are typically decreased by the presence of solid particles. The choice of an operational domain is made more difficult by the flat system and pump head curves, as well as by the solids effect of the pump, which reduces the clear water head and efficiency. Sellgren, et al. [10] investigated how heavy and coarse solid particles affected the head and efficiency of centrifugal pumps. According to their findings, the head reductions were 16 and 11%, respectively, when the crushed ore product was pumped at a concentration by volume of 6 to 8% in pumps with impeller diameters of 0.91m and 1.38m. The efficiency drop was between 18 and 20 percent. The head and efficiency decreases were 23 and 25%, respectively, while the volumetric concentration in the larger pump was 11.5%. The measured head reductions were 1.5 to 2 times greater than what was predicted using numbers from the literature. Efficiency losses were 3 to 3.5 times more severe. Particles with some roundness, frequently brought on by circulatory effects in experimental loop-facilities, have been the main focus of the available criteria. The results presented were only possible with a brief exposure time. With an average particle size of 15000 to 225000 microns, the crushed product's bigger reported reductions are consequently associated with the angularity of its particles. In order to investigate the individual effects of particle size distribution, particle size, specific gravity, solids concentration, and centrifugal pump performance, Kazim et al. [11] carried out tests. They discovered that for a constant spanning the tested range of discharge, there are proportionate losses in pump head and efficiency. At any given flow rate and solids concentration, they also concluded that the relative efficiency loss was typically less than the relative head loss. By incorporating the fine sand into the medium sand or the coarse sand, Ni et al. [12] studied the properties of a slurry pump. By mixing 10% of the fine sand into 25% of the medium sand, they tested eight mixes of them to determine the impact of particle size distribution on the pump performance. They discovered that while the efficiency drop for mixed service is less than for medium sand only, the round black points for the mixture are higher than for the medium sand alone. They also concluded that adding fine sand to medium sand has a different impact than adding fine sand to coarse sand because although fine sand is not as fine as sand or clay particles, it can still improve pump performance.

The performance of the pump can be greatly enhanced by mixing fine sand with coarse sand. Sand-clay slurries' impact on centrifugal slurry pumps' performance characteristics was researched by Sellgren et al. [13]. They noticed that the friction losses in the pipe lines decreased when clay was added to sand, which in turn reduced power usage and pumping head. Sand slurries with volume contents of up to 35% were discovered to have pump water heads and efficiency of up to 30%. For sand to clay mass ratios between 1:4 and 1:6, efficiency and head were reduced by around one-third. The relative motion of the solids and water in the volute zone of the pump is predicted, and comparisons are conducted with design requirements and a mechanistic model method. However, the head, capacity, and power characteristics of two centrifugal slurry pumps using three solid materials with various particle size distributions. They concluded that solids are to blame for the increased losses that occur in the pumps. Additionally, it has been noted that when pump size increases, extra losses brought on by the presence of solids decrease.

4. SUSPENDED SOLID EFFECT

The choosing of pump and designing a slurry system, the performance impact of solids on a centrifugal pump is a key factor. Some slurry handling system designs, however, are focused solely on the performance of clear water, which could result in the failure of establishment. For the design and optimization of a slurry transportation system, the projected head accuracy and efficiency reduction factors for a slurry pump are crucial. To this purpose, it is crucial to understand how the performance of the pump will be impacted by the presence of solids.

For a long time, researchers have been interested in the impact of suspended material on the efficiency of centrifugal slurry pumps. The link between the best efficiency point reduction, particle solids, and concentration of solids up to 32% by volume is provided in a valuable monograph proposed by Stepanoff [14] after reviewing earlier studies. This paper is regarded as the first in-depth investigation of the effectiveness of solid-liquid two-phase centrifugal pumps. It was difficult to determine how solids affected the functioning of the pump despite the prior results showing that they do not absorb, store, or transmit pressure energy. The impact of particles on the performance and head of large centrifugal pumps was studied by Sellgren and Addie [15]. They employed two sands with average particle sizes of 0.25, 1.5, and 6 mm, and a gravel material. According to their findings, the clear water level was reduced by 3.5, 7, and 10%, respectively, when pumped at a solids concentration by weight of 32% in centrifugal pumps with impeller diameters of 1.1 and 1.2 m, at a flow rate that was around 70% of the flow rate at the best efficiency point. The solids impact may relate linearly to the concentration by weight at lower concentrations. Normally, the decrease in clear water efficiency was not as great as the decrease in head. The flow rate generally had a small impact on the solids reduction effect. Nevertheless, it can be thought that the influence is unrelated to the rotary speed. Additionally, it was shown that the solids impact can be significantly influenced by the pump design, including the type of vanes. Additionally, it was shown that the particle size distribution has a significant impact and that the impact of high solids concentrations is complicated.

In larger pumps than in smaller ones, the impact of solids on performance was seen to be less pronounced. The head reduction decreased exponentially with increasing impeller diameter, with an exponent of approximately 0.9. Additional generalizations based on a dimensional analysis technique linked the strong impact of the particle size distribution to a characteristic particle drag coefficient that was calculated as the sum of impacts of each particle size. Sellgren and Addie [16] looked on how solids affected centrifugal slurry pumps' performance. The impact of solids on the head and efficiency of centrifugal medium duty slurry pumps with impeller diameters of 0.3-0.6 m has been studied. Their preliminary findings, which are described here, indicated that pumping sands with average particle sizes of 285-2300 µm at solids concentrations by average weight of 32 to 57% resulted in head reductions of 6-15%. Generally speaking, excepting the highest concentrations and the smallest pumps, the reductions in efficiency were equivalent to or less than the reductions in head. They found that the head and efficiency drop for the medium duty slurry pumps were generally less severe than the figures given for pumps of comparable size. Sellgren and Addie [17] investigated the impact of solids on big slurry pumps working at extremely high slurry concentrations and using impellers with diameters of 0.8 and 1.2 m. In comparison to small pumps, they found that the impact of solids was less noticeable in larger pumps. They concluded that for larger pumps, the head reduction was typically more than the efficiency reduction, and that these two reductions were typically equal for smaller units.

5. PUMP SPEED EFFECT

An essential factor that affects the centrifugal pumps function is the pump's rotational speed. Variations in the rotational speed (N) also affect the break horse power (BHP), head (H), and discharge capacity (Q). The Q to N, H to N, and BHP to N relationships are defined by what are known as the affinity laws, which hold true at any point on the head-capacity curve.

Gandhi, et al.'s [18] experimental investigation of pump characteristics at various pump speeds led to the conclusion that slurry pumps handling water and slurries at low solid concentrations (20% by weight) can use the same head and capacity affinity relations that apply to conventional pumps. These relationships need to be modified for increased solid concentrations by taking the impact of solids into consideration. The link between input power and output power, even for clear water pumps, does not apply to slurry pumps, and considerable speed differences must be rectified.

6. SLIP FACTORS EFFECT

Studies on the performance of centrifugal slurry pumps have previously focused mostly on the increased friction losses in the through flow associated with the two-phase mixtures. Sheth, et al. [19] conducted tests to investigate the impact of different parameters on slip factor and their impact on centrifugal slurry pump performance characteristics. They introduced two non-dimensional parameters for a slip factor correlation.

Three different rates of water and sand slurry were used in the trials. In order to determine the characteristic curves of the pump, measurements of flow rate, slurry density, head created by the pump, and power were taken. For estimating the slip and friction components of the flow, Euler's equations were derived. The recommended non-dimensional groups and the calculated factors slip for centrifugal slurry pumps can be well connected. They concluded that there was a constant relationship between slip factor and impeller rotation and slurry mixture density. Glass beads and sand with sizes ranging from 0.71 to 0.09 mm were used. Since the shut-off power measurements are probably vulnerable to inaccuracies related to the particles settling, or the transient effect if the measurement is made shortly, the slip factor calculated from head-flow rate curves is more reliable than those calculated from power-flow rate curves.

Emissions and carbon footprint associated with centrifugal pump systems can significantly vary under different operating conditions, particularly when handling multiphase flow, which includes mixtures of liquids, gases, and sometimes solids [20-27]. In such conditions, pump performance often declines due to issues like cavitation, flow instabilities, and increased power consumption. These inefficiencies lead to higher energy demands [28-39], consequently increasing greenhouse gas emissions if the energy source is non-renewable. Emissions and carbon footprint associated with centrifugal pump systems are closely linked to their energy source, fuel usage, and operating conditions, especially under multiphase flow scenarios involving liquid-gas or liquid-solid mixtures. These conditions often lead to reduced pump performance due to cavitation, flow instability, and increased mechanical wear, which in turn demand higher energy input to maintain the required output.

When centrifugal pumps are powered by fossil fuel-based systems, such inefficiencies result in elevated fuel consumption and increased greenhouse gas emissions, posing a significant challenge to sustainability. The presence of gas or solid particles in the fluid stream affects the hydraulic characteristics, pushing the pump to operate away from its best efficiency point (BEP), thereby further increasing energy demand and the associated carbon footprint. This not only affects operational cost but also undermines efforts toward achieving energy efficiency and environmental sustainability goals [40-47].

Adopting renewable energy sources such as solar or wind to power pump systems, along with incorporating advanced control strategies and energy-efficient designs [48-59], can significantly reduce fuel dependency and emissions. Moreover, life cycle assessments and sustainable maintenance practices are essential to minimize the overall environmental impact. Optimizing pump performance under multiphase conditions is therefore vital for promoting cleaner, more sustainable industrial operations[60-69].

7. HEAD LOSS EFFECT

Because coarse particles have a higher inertia and cannot accelerate as quickly as the carrier liquid due to their relative motion, the flow of solids through the pump results in corresponding hydraulic losses. It is crucial to understand that fluids have the ability to absorb, store, and transmit pressure energy, which solids suspended in a liquid are unable to do. Additionally, because the liquid is moving more quickly than they are, they cannot transfer their kinetic energy to it. The term "settling-mixtures" often refers to mixtures with a size distribution incorporating bigger particles larger than 0.1 mm approximately. In these mixtures, the liquid and particles will each display unique properties. Pump head and efficiency are decreased as a result of "drag," which occurs as the liquid troughs above the solid particles and the impeller dissipates energy into the carrier fluid. By deducting all of the energy-head losses brought on by the flowing liquid, the head-capacity characteristics of centrifugal slurry pumps are determined from the theoretical characteristics. Using Euler's equation, the theoretical or Euler head increase for an ideal fluid moving through a centrifugal impeller with one infinite number of vanes is calculated as follows:

$$H_{th} = \frac{U_2 V_{w2} - U_1 V_{w1}}{g}$$

Gandhi, et al. [9] devised a methodology that relied on a loss analysis process to forecast how well centrifugal pumps handling slurries would function. Their approach considers the slurry pump's different structure from the liquid pump. Although within a +12% error zone, this technique provides reliable forecasts. These forecasts require precise and detailed information about pump shape, which is difficult to obtain. Vocaldo and Charls [70]classified the head loss in three categories:

$$\Delta \mathbf{h_m} = I_J + I_L + I_S$$

Where IL is the head loss or pressure gradient that would be possible if the carrier liquid flowed alone at the same velocity as the slurry, and Ij is the pressure gradient that contributes the energy needed to maintain the solid particles in a state of slurry. This pressure gradient also reflects the increase in density and viscosity of the carrier liquid, IL is the head loss or pressure gradient that would occur if the carrier liquid moved at the same speed as the slurry alone, this pressure gradient provides the energy needed to keep the solid particles suspended in the face of gravity. With an increase in slurry velocity, head losses rise as well. Roco, et al. [71] investigation into centrifugal slurry pumps' casing head loss. They concluded that the energy loss in the flowing liquid-solid combination and the parties' interactions with the casing wall are what because the head losses in slurry pump casings. Pump impeller boundary conditions are affected by the casing shape, pump rotational speed, flow rate, solids characteristics, concentration, and inflow. The method can be applied for parametric analyses and casing shape optimization, accounting for both erosive wear and energy dissipation.

The periodic flow in the casing induced by the finite number of impeller blades is averaged throughout the normal time interval for the governing equations. Comparing the performances of three centrifugal slurry pumps with quasi-spiral, semi- annular, and annular casing at different flow rates provides an illustration of the impact of casing shape on head losses. The overall head loss is demonstrated to be significantly influenced by the flow that was recalculated between the impeller shrouds and the casing tongue. The flow results can also be combined to determine the impeller's thrust and casing wear, as well as to optimize the casing's size.

8. TIP CLEARANCE EFFECT

Centrifugal pumps that handle solid-liquid mixtures have traditionally made considerable use of both shrouded and unshrouded impellers. Due to their comparatively low disc friction losses, low production costs, and ease of coating their surfaces to obtain good wear resistance, unshrouded impeller are preferred in many real-world applications. Additionally, they are suitable for pumping suspensions. However, tip clearance losses become crucial when unshrouded impellers are used in pumps. It is commonly known that the tip clearance has a significant impact on how well spinning machines work. Tip Clearance is the distance between the vane tips of an impeller with partial shrouding and the front casing. Numerous turbo machines have unshrouded impellers, and the flow leakage from the blade tips is an unavoidable problem that reduces machine performance. Although tip clearance impacts on pump performance have been researched for a long time and the need for accurate information is growing, there is presently no exact mechanism for predicting these effects. Instead, models must be developed with the aid of test data in order to quantify these impacts.

Numerous strategies have been put out for tip leakage flow modelling in order to forecast tip clearance losses. The loss equations provided in the literature are based on numerous assumptions about the loss process or they are derived from scant experimental data. Additionally, the majorities of articles in the subject focus either on solid effects on pump performance or tip clearing effects with water/gas. Unshrouded impeller centrifugal pumps' operating point is heavily influenced by the tip clearance value. The planned tip clearance and the actual tip clearance typically differ because of manufacturing and assembly tolerances as well as clearance enlargements brought on by wear. As a result, the operating conditions fall short of the anticipated pump performance. Engine and Gur [72] conducted experiments to investigate the impact of solids in an unshrouded centrifugal pump impeller when it handled water and solid-water mixes by altering tip clearance. Although tip clearance effects have been a focus of research for a long time, the process underlying tip clearance leakage loss for combined single- and two-phase flows through the pumps still needs to be clarified. They concluded that the process for tip clearance loss while pumping mixtures appears to be similar to that of single-phase pumping and that a constant decline in pump performance is shown for varying tip clearance. The head reduction factor (RH) seems to be virtually completely unaffected by changes in tip clearance. A modest declining tendency is seen, nevertheless. Utilizing data that was both newly acquired and previously published in the literature, a new correlation to forecast the head loss caused by the presence of solids in pumped water has been constructed and examined. The proposed correlation has provided results that are more accurate than those of other, more widely available correlations.

$$\mathbf{R_H = 0.11\ C_W\ (S\text{-}1)^{0.64}\ Ln\ (44d_w}$$

The difference between the estimated and actual head reduction factor falls between (-20% and +15%). The current correlation is found to be relevant to pumps with shrouded or unshrouded impellers and metal and rubber linings.

9. PUMP GEOMETRY EFFECT

Pump geometry, including inlet and outlet vane angles, the number of impeller vane, outlet width, vane material, and vane shape, all have an impact on how well centrifugal slurry pumps work. Walker, et al. [73] investigated how a centrifugal pump's performance characteristics when handling solids in suspension are influenced by the geometry of the pump. Inlet/outlet vane angles, vane number, vane shape, and outlet vane width were the parameters that were evaluated. They concluded that the vane form significantly affects the declines in pump head and efficiency. Gandhi, et al. [10] looked into the capabilities of two different-sized centrifugal slurry pumps for handling mixtures of various solid materials. Their investigation on pumps essentially proved that larger pumps resulted in less incremental head loss for slurries.

9.1. EFFECT OF SOLIDS ON CAVITATION CHARACTERISTICS

Never allow the pressure in the line of suction to drop below the saturated vapor pressure (Pv) of the liquid to prevent cavitation in the pumping systems. Pressure dips happen as a result of suction pipe losses and localized flow acceleration near the impeller's input. The local suction head less and the liquid's vapor pressure head at the pumping temperature are therefore the sources of energy that can be used to force the liquid via the suction pipe and suction water way of the pump into the impeller. The net positive suction head available is the resultant available head as measured at the pump's suction opening, also known as NPSH.

$$\mathbf{NPSHA} = \frac{P_{atm}}{\rho g} - \frac{P_1}{\rho g} \pm Z_0 - h_f$$

Where: P_{atm} is the atmospheric pressure in barometric or gauge units, ρ is a density of pumped liquid, g is acceleration due to gravity, Z0, is an elevation head (suction head/suction lift) and hf is friction head loss for the flow rate benign considered between the existing absolute suction head and vapor pressure at the given temperature. NPSHR, a characteristic that differs from other characteristics and is dependent on the pump's design, stands for net positive suction head required by the pump. It is achieved by doing a centrifugal pump test on water, and it is the smallest difference between the suction head and the vapor pressure necessary for the pump to function properly. According to standard procedure, the NPSHR figures on pump performance curves represent levels where a single stage pump's total head will be lowered by 3% of its full declared value[74-76]. Together, NPSHA and NPSHR values fluctuate as the pump flow rate varies at a particular speed. The performance factors for slurry pumps. He demonstrated that the net positive suction head required by the slurry pump cannot be assumed to be the same as that for water and that further modifications are necessary by using one sand and three gravel materials with average particle sizes of 0.2, 0.96, 1.8, and 6.15 mm, respectively. Mashin [77] performed studies in the lab using a 5-inch end suction slurry pump with a 330 mm impeller that could handle sand slurries with a 1.15 specific gravity and a mean particle diameter of 1 mm. He concluded that there was no need for an additional solid’s adjustment because the NPSH needed by centrifugal pumps for this kind of slurries had the same value as that for water. It indicates that when handling slurry, cavitation in the pump begins at a higher suction pressure than on water. The similar conclusion was reached by Herbich and Cooper [78] after testing dredge pumps for settling slurries. In a laboratory test, the suction performance of a 5-inch end suction slurry pump handling sand and gravel slurries with a range of solid particle sizes. During tests, the operating points of the pumps ranged from 80% to 120% of the flow rate at which they were at their best efficiency. The density of the slurry varied between 1025 and 1280 kg/m3. The test rig was set up as a closed loop with the ability to modify pressure by removing air from the system. They concluded that there was no need for further correction because the net positive suction head needed by centrifugal pumps was the same as that needed for water. A 4-inch side inlet slurry pump with a variety of impellers, including closed type impellers with 4 and 6 vanes and a channel-type two-vane impeller, was put through testing. They concluded that slurry pump suction performance should differ from that on water while pumping heavy medium of magnetite. The impact of solids on NPSH during slurry pumping was researched by Roundnev [77]. While working with sand and gravel slurries including a range of particle sizes, he employed a 5-inch end suction slurry pump. He concluded that the net positive suction head needed by the pump could not be calculated similarly to that needed for water. As a result, several corrective techniques must be used. The cavitation characteristics of centrifugal pumps were researched by Addie et al. [79]. They concluded that a 20-inch slurry pump requires a net positive suction head that is 1.5 times greater than what is needed for water pumping.

From an examination of the prior literature, it can be shown that there is conflicting information regarding the impact of several parameters, such as solid concentration and impeller speed, on the performance traits of centrifugal slurry pumps. To achieve dependable and energy-efficient operation, it is necessary to thoroughly investigate the impact of solids on pump head and power consumption. However, there aren't a lot of experimental data accessible in the literature, and it's still difficult to establish any trustworthy correlation or method for determining head reduction factor over a broad range of solids' physical characteristics and operating circumstances.

Additionally, nothing is known regarding the impact of broad particle size distribution, breakdown, cavitation inception, and pattern when pumping slurry on the properties of centrifugal slurry pumps. As a result, measurements are required to confirm these impacts. An experimental test rig is created to fulfil these objectives.

9.2. THE EFFECT OF SLURRY FLOW ON PUMP LIFT

EL-Agouz and Hagar [80] conducted experiments to investigate The effect of slurry flow on pump lifetime is a critical consideration for industries that rely on pumping systems, especially those dealing with abrasive materials. Slurry, a mixture of solid particles suspended in a liquid, presents unique challenges that can significantly influence the durability and operational lifespan of pumps. As slurry flows through a pump, the solid particles exert mechanical forces on the pump‘ s internal components, leading to wear and tear that can shorten its lifespan.

One of the primary factors affecting pump lifetime in slurry applications is the abrasive nature of the solid particles. Larger and harder particles can cause increased erosion on the pump’s impeller, casing, and other internal surfaces. Over time, this erosion can lead to reduced pump efficiency and performance, as well as the potential for catastrophic failure if critical components become compromised. Regular wear can also lead to misalignment and vibrations, which further contribute to the degradation of pump components. Additionally, the concentration and density of the slurry play significant roles in determining the pump’s operational life. Higher concentrations of solids increase the load on the pump and can lead to more severe wear patterns. Similarly, denser slurries can create challenges for maintaining consistent flow rates, which may result in cavitation—a phenomenon where vapor bubbles form and collapse within the pump. Cavitation can cause significant damage to the impeller and other components, further reducing the pump‘s lifespan.

Another important consideration is the impact of slurry flow on pump vibrations. As previously mentioned, irregular flow patterns caused by solid particles can induce higher vibration levels. Excessive vibrations can lead to premature bearing failure and seal wear, ultimately reducing the operational life of the pump. Furthermore, the interactions between the slurry and the pump components can exacerbate these vibration issues, leading to a cyclical pattern of increasing wear and decreasing reliability.

To mitigate the negative effects of slurry flow on pump lifetime, it is essential to implement effective design and maintenance strategies. Selecting pumps specifically designed for handling slurries, such as those with robust materials and erosion-resistant features can significantly enhance durability. Regular monitoring and maintenance, including inspections for wear, alignment checks, and vibration analysis, can help identify potential issues before they escalate into significant problems.

9.3. THE EFFECT OF SLURRY FLOW ON PUMP VIBRATION

Aleksandrov and Menshikov [81] conducted experiments to investigate the impact of slurry flow on pump vibration is a crucial consideration for ensuring optimal pump performance and longevity, particularly in industries that deal with abrasive materials. Slurry, which is essentially a mixture of solid particles suspended in a liquid, presents distinct challenges for pump operations due to the effects of these solid particles on mechanical components. As slurry moves through the pump, the interaction between the solid particles and the pump surfaces can lead to increased wear and tear on internal components, causing imbalances in the rotating parts of the pump. This imbalance is a significant factor that contributes to elevated levels of vibration, which can be detrimental to the pump’s functionality and lifespan.

Several factors influence the degree of vibration caused by slurry flow, including the size, concentration, and density of the solid particles present in the mixture. Larger and heavier particles tend to create more significant disturbances in the flow, while higher concentrations of solids can result in uneven flow patterns within the pump. These irregularities can amplify the intensity of the vibrations experienced during operation. When the flow is uneven, it can lead to fluctuations in pressure and increased turbulence, which can further exacerbate vibration issues. The consequences of heightened vibration due to slurry flow are numerous and can severely impact the operational efficiency of the pump. One of the primary issues associated with increased vibration is the potential for premature bearing failure. Bearings are critical components in a pump, and when they are subjected to excessive vibrations, they can wear out more quickly than anticipated, leading to costly repairs and unplanned downtime. Additionally, vibrations can lead to seal wear, which compromises the pump‘s ability to maintain pressure and can result in leaks. Damage to the pump‘s impeller and casing can also occur as a result of excessive vibrations, further contributing to operational inefficiencies and increased maintenance requirements.

Over time, if left unaddressed, excessive vibrations can significantly reduce the overall efficiency of the pump. This reduction in efficiency not only impacts the performance of the pump but can also lead to increased energy consumption, as the pump may require more power to operate effectively under strained conditions. Furthermore, the resulting downtime for repairs can be costly, both in terms of lost productivity and the expense of maintenance services. Another critical aspect to consider is the interaction between slurry particles and cavitation within the pump. Cavitation occurs when there is a rapid drop in pressure that leads to the formation of vapor bubbles within the liquid. These bubbles can collapse violently, creating shock waves that contribute to further damage to the pump’s components. The presence of solid particles in the slurry can complicate this issue, as they may exacerbate cavitation effects and increase the severity of vibration-related problems.

In light of these considerations, it becomes evident that understanding and managing the effect of slurry flow on pump vibration is essential for maintaining optimal pump performance, extending the equipment‘ s operational life, and minimizing overall maintenance costs. Implementing effective design strategies that account for the unique challenges posed by slurry flow is crucial. Additionally, regular maintenance and monitoring can help identify potential vibration issues before they escalate, ensuring that the pump operates smoothly even under demanding conditions. By prioritizing these practices, industries can enhance the reliability and efficiency of their pumping systems, ultimately leading to improved operational outcomes.

9.4. THE EFFECT OF SLURRY FLOW ON PUMP MISALIGNMENT

X. F. Gao and W. D. Shi [84] conducted experiments to investigate the effect of slurry flow on pump misalignment is a crucial consideration in maintaining pump performance and reliability, particularly in applications involving abrasive materials. When a pump operates with slurry, the unique properties of the slurry can exacerbate existing alignment issues or create new ones. Misalignment occurs when the pump shaft is not properly aligned with the motor or drive, leading to uneven loading on the bearings and other components. This can be aggravated by the uneven flow patterns caused by solid particles within the slurry, which may induce vibrations and dynamic forces that further disrupt alignment. As slurry flows through the pump, larger solid particles can create additional stresses on the pump casing and mounting points, potentially shifting the pump‘s position and increasing the risk of misalignment. Misalignment in pumps handling slurry can lead to several operational challenges, including increased wear on bearings and seals, higher energy consumption, and reduced efficiency. Over time, the strain caused by misalignment can result in premature failure of components, necessitating costly repairs and unplanned downtime. Additionally, the interaction between slurry flow and pump components can exacerbate vibration issues, which may further destabilize the pump assembly. To mitigate these problems, it is essential to regularly monitor and maintain proper alignment, implement robust design strategies that accommodate the challenges posed by slurry handling, and ensure thorough inspections are conducted during maintenance activities. By addressing the effect of slurry flow on pump misalignment, operators can enhance pump reliability, optimize performance, and extend the operational lifespan of their equipment.

Conversely, optimizing pump design, applying variable speed drives, and using renewable energy sources can enhance efficiency and significantly reduce fuel consumption and emissions[82-88]. Sustainable operation also depends on regular maintenance and monitoring, ensuring the pump runs near its best efficiency point, thereby supporting energy conservation and environmental sustainability goals.

10. Conclusion:

This comprehensive review has highlighted the multifaceted influence of various parameters on the performance characteristics of centrifugal slurry pumps. It has been demonstrated that solid concentration, particle size and distribution, slurry composition, pump speed, and slip factors all significantly affect pump head, efficiency, and power requirements. While centrifugal slurry pumps remain vital for the hydraulic transportation of solids in mining, dredging, and industrial applications, their performance is markedly distinct from that of conventional clear-water pumps due to the complex interactions between solid particles and fluid dynamics. Notably, higher concentrations and coarser particles tend to decrease head and efficiency, with larger pumps generally exhibiting lower sensitivity to such degradations. Advances in experimental and analytical methodologies have provided better predictive tools, such as correlations involving Reynolds numbers, slip factors, and particle drag coefficients. However, practical limitations in testing and variability in slurry compositions necessitate ongoing refinement of pump design and performance prediction models. Optimizing the reliability and energy efficiency of slurry handling systems thus depends on a deep understanding of these influencing factors, reinforced by targeted experimental data and robust analytical models tailored to slurry-specific challenges.

References:

[1] C. I. Walker and A. Goulas, "Performance characteristics of centrifugal pumps when handling non-Newtonian homogeneous slurries," *Proceedings of the Institution of Mechanical Engineers, Part A: Power and Process Engineering,* vol. 198, pp. 41-49, 1984.

[2] M. Roco, M. Marsh, G. Addie, and J. Maffett, "Dredge pump performance prediction," *Journal of pipelines,* vol. 5, pp. 171-190, 1986.

[3] G. Wilson, "The effects of slurries on centrifugal pump performance," 1987.

[4] A. Sellgren, T. Turner, and G. Addie, "Determination of the effect of solids on centrifugal slurry pumps," in *Fifth Annual AIME Regional Phosphate Conference, Lokeland, Florida*, 1990.

[5] K. C. Wilson, G. R. Addie, A. Sellgren, and R. Clift, *Centrifugal pumps*: Springer, 2006.

[6] K. Kazim, B. Maiti, and P. Chand, "A correlation to predict the performance characteristics of centrifugal pumps handling slurries," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* vol. 211, pp. 147-157, 1997.

[7] F. Ni, W. Vlasblom, and A. Zwartbol, "Effect of high solids concentration on characteristics of a slurry pump," in *Hydrotransport 14, Maastricht*, 1999, pp. 141-149.

[8] B. K. Gandhi, S. Singh, and V. Seshadri, "Improvements in the prediction of performance of centrifugal slurry pumps handling slurries," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* vol. 214, pp. 473-486, 2000.

[9] B. K. Gandhi, S. Singh, and V. Seshadri, "Performance characteristics of centrifugal slurry pumps," *J. Fluids Eng.,* vol. 123, pp. 271-280, 2001.

[10] A. Sellgren, D. Luther, and G. Addie, "Effect of coarse and heavy solid particles on centrifugal pumps head and efficiency," in *Proc. 47th Canadian Chemical Engineering Conference*, 1997, pp. 5-8.

[11] K. Kazim, B. Maiti, and P. Chand, "Effect of particle size, particle size distribution, specific gravity and solids concentration on centrifugal pump performance," *Powder Handling & Processing,* vol. 9, pp. 27-32, 1997.

[12] F. Ni, W. Vlasblom, and A. Zwartvol, "An Experimental Investigation on Characteristics of a Slurry Pump," *Hydrotransport-14, BHRA group,* 1999.

[13] A. Sellgren, G. Addie, and S. Scott, "The effect of sand-clay slurries on the performance of centrifugal pumps," *The Canadian journal of chemical engineering,* vol. 78, pp. 764-769, 2000.

[14] A. J. Stepanoff, *Pumps and Blowers: Two-phase Flow: Flow and Pumping of Solids in Suspension and Fluid Mixtures*: J. Wiley & sons, 1965.

[15] A. Sellgren and G. Addie, "Effect of solids on large centrifugal pump head and efficiency," *Proc. The CEDA Dredging Day,* 1989.

[16] A. Sellgren and G. Addie, "Effects of Solids on The Performance of Centrifugal Slurry Pumps," in *10th colloquium", Massengut Transport Durch Rohrleitungen," in Meschede, Germany*, 1992.

[17] A. Sellgren and G. Addie, "Solids effect on the characteristics of centrifugal slurry pumps," in *Proc. 12th Int. Conference on the Hydraulic Transport of Solids in Pipes*, 1993.

[18] B. K. Gandhi, S. Singh, and V. Seshadri, "Effect of speed on the performance characteristics of a centrifugal slurry pump," *Journal of Hydraulic Engineering,* vol. 128, pp. 225-233, 2002.

[19] K. Sheth, G. Morrison, and W. Peng, "Slip factors of centrifugal slurry pumps," 1987.

[20] M. Elkelawy, E. El Shenawy, H. Alm-EldinBastawissi, I. A. Mousa, and M. M. A.-R. Ibrahim, "Analyzing the Influence of Design and Operating Conditions on Combustion and Emissions in Premixed Turbulent Flames: A Comprehensive," *Journal of Engineering Research (ERJ,* vol. 8, p. 15, 2024.

[21] M. H. Aboubakr, M. Elkelawy, H. A.-E. Bastawissi, and A. R. Abd Elbar, "Chemical Kinetic Investigation: Exploring the Impact of Various Concentrations of HHO Gas with a 40% Biodiesel/Diesel Blend on HCCI Combustion," *Journal of Engineering Research,* vol. 8, 2024.

[22] M. Elkelawy, M. Bassuoni, H. A.-E. Bastawissi, and S. I. Haiba, "Effect of Dual-fuelled CNG and Gasoline on Spark Ignition engine performance and Emissions behaviors at different loads," *Journal of Engineering Research,* vol. 8, p. 18, 2025.

[23] M. ELKELAWY, A. M. SAEED, and H. SELEEM, "Egypt's Solar Revolution: A Dual Approach to Clean Energy with CSP and PV Technologies," *Pharos Engineering Science Journal (PES),* vol. 1, pp. 29-37, 2025.

[24] A. A. El-Nagar, M. M. El-Sheekh, M. Elkelawy, and H. A.-E. Bastawissi, "Enhancing diesel engine performance and emissions with innovative Ethanol-Surfactant blends in Biodiesel: Unveiling insights through fractional factorial design," *Sustainable Energy Technologies and Assessments,* vol. 73, p. 104169, 2025.

[25] M. Elkelawy, H. A.-E. Bastawissi, M. O. Elsamadony, and A. Salem, "Enhancing Diesel Engine Performance by Directly Injecting Blends of Ammonium Hydroxide and Including Liquid Petroleum Gas as a Partially Premixed Charge," *Journal of Engineering Research (ERJ,* vol. 8, p. 16, 2024.

[26] D. S. Flaih, M. F. Al-Dawody, M. Elkelawy, W. Jamshed, A. Abd-Elmonem, N. S. E. Abdalla*, et al.*, "Experimental and numerical study on the characteristics of gasoline engine powered by gasoline blended with water ammonia solution," *Fuel,* vol. 387, p. 134333, 2025.

[27] M. Elkelawy, H. A.-E. Bastawissi, A. Abou El-Yazied, and S. El-malla, "Experimental Investigation on Combustion and Emission Characteristics of Co-combustion of Pulverized Biomass with Diesel Fuel in an Industrial Burner," *Journal of Engineering Research,* vol. 8, p. 17, 2024.

[28] M. H. Aboubakr, H. A.-E. Bastawissi, and A. R. Abd Elbar, "Exploring the Influence of Various Factors, Including Initial Temperatures, Equivalence Ratios, and Different Biodiesel/Diesel Blend Ratios, on Homogeneous Charge Compression Ignition (HCCI) Combustion," *Journal of Engineering Research (ERJ),* vol. 8, p. 8, 2024.

[29] M. ELKELAWY, W. M. EL-ASHMAWY, A. W. AHMED, and H. SELEEM, "Feasibility Study of Geothermal Energy Development in Egypt: Power Generation and Direct Use in Gulf of Suez, Red Sea, and Western Desert," *Pharos Engineering Science Journal (PES),* vol. 1, pp. 39-50, 2025.

[30] M. Elkelawy, H. Alm-EldinBastawissi, E. El Shenawy, and M. M. Ouda, "A Greening the Diesel: Vegetable Oil Biodiesel Blends for Cleaner Emissions and Improved Direct Injection Diesel Engine performance," *Journal of Engineering Research,* vol. 8, p. 16, 2025.

[31] M. Elkelawy, H. Bastawissi, A. Abdel-Rahman, A. Abou-elyazied, and S. El-malla, "The Impact of Incorporating Varying Proportions of Sugar Beet Waste on the Combustion Process and Emissions in Industrial Burner Fuelled with Conventional Diesel Fuel," in *Journal of Physics: Conference Series*, 2024, p. 012005.

[32] M. Elkelawy, A. Walaa, and M. M. Sayed, "Innovative Integration of Hydropower and Thermal Energy for Combined Heat and Power Production: A Comprehensive," *Pharos Engineering Science Journal (PES),* vol. 1, p. 11, 2025.

[33] M. Elkelawy, H. A.-E. Bastawissi, M. O. Elsamadony, and A. Salem, "Investigation into the Impact of Ammonia Hydroxide on Performance and Emissions in Compression Ignition Engines Utilizing Diesel/Biodiesel Blends," *Journal of Engineering Research (ERJ),* vol. 8, p. 21, 2024.

[34] H. Alm-EldinBastawissi, M. Elkelawy, M. O. Elsamadony, and M. Ghazaly, "Performance and Emissions Characteristics of Multi-Cylinder Direct Injection Diesel Engine Fuelled with Diesel/Biodiesel and Toluene Additives," *Journal of Engineering Research,* vol. 8, pp. 29-37, 2025.

[35] M. Elkelawy, E. El Shenawy, H. A.-E. Bastawissi, M. M. Shams, E. PV, D. Balasubramanian*, et al.*, "Predictive modeling and optimization of a waste cooking oil biodiesel/diesel powered CI engine: an RSM approach with central composite design," *Scientific Reports,* vol. 14, pp. 1-13, 2024.

[36] M. Elkelawy, H. A.-E. Bastawissi, E. El Shenawy, and M. Soliman, "A Quantitative Analysis of the Commercial-Additive Effects on Diesel Engine Combustion and Emissions Characteristics," *Pharos Engineering Science Journal (PES),* vol. 1, p. 25, 2025.

[37] M. Elkelawy, W. M El-Ashmawy, and S. M. Ahmed, "State of the Art in Concentrated Solar Power: Latest Technological Advancements and Innovations in Efficiency and Energy Storage," *Pharos Engineering Science Journal,* vol. 1, pp. 17-28, 2025.

[38] M. Elkelawy, H. Bastawissi, E. A. E. Shenawy, and M. M. Ouda, "A Technical Survey on the Impact of Exhaust Gas Recirculation and Multifuel Blends on Diesel Engine Performance and Emission Characteristics," *Journal of Engineering Research,* vol. 8, p. 11, 2024.

[39] M. ELKELAWY, Z. A. ATTA, and H. SELEEM, "Technological Advances, Efficiency Optimization, and Challenges in Wind Power Plants: A Comprehensive Review," *Pharos Engineering Science Journal (PES),* vol. 1, p. 10, 2025.

[40] M. M. El-Sheekh, A. A. El-Nagar, M. ElKelawy, and H. A.-E. Bastawissi, "Bioethanol from wheat straw hydrolysate solubility and stability in waste cooking oil biodiesel/diesel and gasoline fuel at different blends ratio," *Biotechnology for Biofuels and Bioproducts,* vol. 16, p. 15, 2023/02/01 2023.

[41] M. Elkelawy, H. A.-E. Bastawissi, A. M. Radwan, M. T. Ismail, and M. El-Sheekh, "Chapter 15 - Biojet fuels production from algae: conversion technologies,

characteristics, performance, and process simulation," in *Handbook of Algal Biofuels*, M. El-Sheekh and A. E.-F. Abomohra, Eds., ed: Elsevier, 2022, pp. 331-361.

[42] M. Elkelawy, H. A.-E. Bastawissi, E. El Shenawy, and M. Soliman, "Effect of Organic Compounds Additives for Biodiesel Fuel blends on Diesel Engine Vibrations and Noise Characteristics," *Journal of Engineering Research (ERJ,* vol. 8, p. 22, 2024.

[43] M. Elkelawy, E. A. El Shenawy, H. A. E. Bastawissi, and I. A. El Shennawy, "The effect of using the WCO biodiesel as an alternative fuel in compression ignition diesel engine on performance and emissions characteristics," *Journal of Physics: Conference Series,* vol. 2299, p. 012023, 2022/07/01 2022.

[44] M. Elkelawy, E. El Shenawy, H. Alm-EldinBastawissi, I. A. Mousa, and M. M. A.-R. Ibrahim, "Effects of Fuel Equivalence Ratio and Swirl Vane Angles on Premixed Burner Turbulent Flame Combustion Characteristics," *Journal of Engineering Research,* vol. 7, p. 15, 2024.

[45] M. Elkelawy, H. A.-E. Bastawissi, M. O. Elsamadony, and A. S. Abdalhadi, "Engine Performance and Emissions Improvement Study on Direct Injection of Diesel/Ammonia Dual Fuel by Adding CNG as Partially Premixed Charge," *Journal of Engineering Research,* vol. 7, p. 12, 2024.

[46] E. El Shenawy, H. A.-E. Bastawissi, and M. M. Shams, "Enhancement of the performance and emission attributes for the diesel engine using diesel-waste cooking oil biodiesel and graphene oxide nanofluid blends through response surface methodology," *Mansoura Engineering Journal,* vol. 49, p. 8, 2024.

[47] M. Elkelawy, "Experimental Investigation of Intake Diesel Aerosol Fuel Homogeneous Charge Compression Ignition (HCCI) Engine Combustion and Emissions," *Energy and Power Engineering,* vol. Vol.06No.14, p. 14, 2014.

[48] Y. Mohamed, F. Muhammad, Ezzat, M. Mohamed A, E. Medhat, and M. Y. Ismail, Ismaiel, "Experimental Investigation of the Performance and Exhaust Emissions of a Spark-Ignition Engine Operating with Different Proportional Blends of Gasoline and Water Ammonia Solution," *Journal of Engineering Research,* vol. 5, 2021.

[49] E. Medhat, A. E. El- Shenawy, A. Hagar, El-Din Moham, and K. Salma, Abd-AlMonem, "Experimental Investigation on Spray Characteristics of Waste-Cooking-Oil Biodiesel/Diesel Blends at Different Injection Parameters," *Engineering Research Journal (ERJ),* vol. 4, 2019.

[50] M. ElKelawy, H. A.-E. Bastawissi, E.-S. A. El-Shenawy, H. Panchal, K. Sadashivuni, D. Ponnamma*, et al.*, "Experimental investigations on spray flames and emissions analysis of diesel and diesel/biodiesel blends for combustion in oxy-fuel burner," *Asia-Pacific Journal of Chemical Engineering,* vol. 14, p. e2375, 2019.

[51] J. G. Vaghasia, J. K. Ratnadhariya, H. Panchal, K. K. Sadasivuni, D. Ponnamma, M. Elkelawy*, et al.*, "Experimental performance investigations on various orientations of evacuated double absorber tube for solar parabolic trough concentrator," *International Journal of Ambient Energy,* vol. 43, pp. 492-499, 2022/12/31 2022.

[52] M. E. P. D. Eng and I. A. M. Eng, "Experimental Study on the Impact of Secondary Air Injection and different swirl van angles on Premixed Turbulent Flame Propagation and Emission Behaviors," *Journal of Engineering Research (ERJ),* vol. 7, 2024.

[53] H. A. El-Din, M. Elkelawy, and Z. Yu-Sheng, "HCCI engines combustion of CNG fuel with DME and H 2 additives," *SAE Technical Paper 2010-01-1473,* 2010.

[54] S. Vivek, K. Srinivasan, B. Sharmila, Y. Dharshan, H. Panchal, M. Suresh*, et al.*, "An Improved Quality Inspection of Engine Bearings Using Machine Vision Systems," *Smart and Sustainable Manufacturing Systems,* vol. 6, pp. 86-98, 2022.

[55] M. H. Aboubakr, M. Elkelawy, H. A.-E. Bastawissi, and A. R. El-Tohamy, "The influence of using HHO with sunflower and soybean oil biodiesel/diesel blend on PCCI engine characteristics," *Journal of Engineering Research,* vol. 7, p. 15, 2024.

[56] A. M. Elbanna, X. Cheng, C. Yang, M. Elkelawy, and H. Alm-Eldin Bastawissi, "Investigative research of diesel/ethanol advanced combustion strategies: A comparison of Premixed Charge Compression Ignition (PCCI) and Direct Dual Fuel Stratification (DDFS)," *Fuel,* vol. 345, p. 128143, 2023/08/01/ 2023.

[57] M. M. El-Sheekh, A. A. El-Nagar, M. ElKelawy, and H. A.-E. Bastawissi, "Maximization of bioethanol productivity from wheat straw, performance and emission analysis of diesel engine running with a triple fuel blend through response surface methodology," *Renewable Energy,* vol. 211, pp. 706-722, 2023/07/01/ 2023.

[58] H. Alm ElDin Mohamad, M. Elkelawy, and O. A. I. HENDAWI, "An overview of the Effect of using HHO on Spark ignition and direct injection engines combustion, performances, and emissions characteristics," *Journal of Engineering Research,* vol. 6, pp. 240-246, 2022.

[59] M. H. Aboubakr, M. Elkelawy, H. A.-E. Bastawissi, and A. R. El-Tohamy, "A technical survey on using oxyhydrogen with biodiesel/diesel blend for homogeneous charge compression ignition engine," *Journal of Engineering Research (ERJ,* vol. 8, 2024.

[60] M. Elkelawy, H. Alm ElDin Mohamad, A. K. Abdel-Rahman, A. Abou Elyazied, and S. Mostafa El Malla, "Biodiesel as an Alternative Fuel in Terms of Production, Emission, Combustion Characteristics for Industrial Burners: a Review," *Journal of Engineering Research,* vol. 6, pp. 45-52, 2022.

[61] H. Thakkar, K. k. Sadasivuni, P. V. Ramana, H. Panchal, M. Suresh, M. Israr*, et al.*, "Comparative analysis of the use of flash evaporator and solar still with a solar desalination system," *International Journal of Ambient Energy,* vol. 43, pp. 1561-1568, 2022/12/31 2022.

[62] A. M. Elbanna, C. Xiaobei, Y. Can, M. Elkelawy, and H. A.-E. Bastawissi, "A comparative study for the effect of different premixed charge ratios with conventional diesel engines on the performance, emissions, and vibrations of the engine block," *Environmental Science and Pollution Research,* vol. 30, pp. 106774-106789, 2023/10/01 2023.

[63] M. Elkelawy, H. Alm ElDin Mohamad, M. Samadony, A. M. Elbanna, and A. M. Safwat, "A Comparative Study on Developing the Hybrid-Electric Vehicle Systems and its Future Expectation over the Conventional Engines Cars," *Journal of Engineering Research,* vol. 6, pp. 21-34, 2022.

[64] H. A. E.-D. Bastawissi and M. Elkelawy, "Computational Evaluation of Nozzle Flow and Cavitation Characteristics in

a Diesel Injector," *SAE International Journal of Engines,* vol. 5, pp. 1605-1616, 2012.

[65] A. Hagar, El-Din, Y.-S. 张. Zhang, and E. Medhat, "A Computational Study of Cavitation Model Validity Using a New Quantitative Criterion," *Chinese Physics Letters,* vol. 29, p. 064703, 2012/06/01 2012.

[66] A. E. Kabeel, M. Elkelawy, H. A. El-Din, A. M. El-Banna, R. Sathyamurthy, and N. Prakash, "COMPUTATIONAL STUDY OF DIFFERENT TURBULENCE MODELS FOR AIR IMPINGEMENT JET INTO MAIN AIR CROSS STREAM," vol. 46, pp. 459-475, 2019-10-16 2019.

[67] M. Elkelawy, H. Alm ElDin Mohamad, E. Abd Elhamid, and M. A. El-Gamal, "A Critical Review of the Performance, Combustion, and Emissions Characteristics of PCCI Engine Controlled by Injection Strategy and Fuel Properties," *Journal of Engineering Research,* vol. 6, pp. 96-110, 2022.

[68] H. Bastawissi, Z. Yu-Sheng, M. Elkelawy, and A. Bastawissi, "Detailed 3D-CFD/chemistry of CNG-hydrogen blend in HCCI engine," SAE Technical Paper 0148-7191, 2010.

[69] M. Elkelawy, H. A.-E. Bastawissi, A. K. Abdel-Rahman, A. Abou El-Yazied, and S. Mostafa El malla, "Effect of multifunctional fuel additive in diesel/waste oil biodiesel blends on industrial burner flame performance and emission characteristics," *International Journal of Ambient Energy,* vol. 44, pp. 1382-1395, 2023/12/31 2023.

[70] J. Volcado and M. Charles, "Prediction of pressure gradient for the horizontal turbulent flow of slurries, proceeding of the 2nd international conference on the hydraulic transport of solids in pipes," *Coventry, UK, paper C,* vol. 1, pp. 1-12, 1972.

[71] M. Roco, P. Nair, and G. Addie, "Casing headloss in centrifugal slurry pumps," 1986.

[72] T. Engin and M. Gur, "Performance characteristics of a centrifugal pump impeller with running tip clearance pumping solid-liquid mixtures," *J. Fluids Eng.,* vol. 123, pp. 532-538, 2001.

[73] C. Walker, P. Wells, and C. Pomat, "The effect of impeller geometry on the performance of centrifugal slurry pumps," in *4th International Conference on Bulk Materials, Storage, Handling and Transportation: 7th International Symposium on Freight Pipelines; Preprints of Papers*, 1992, pp. 97-101.

[74] S. El-din H. Etaiw, M. Elkelawy, I. Elziny, M. Taha, I. Veza, and H. Alm-Eldin Bastawissi, "Effect of nanocomposite SCP1 additive to waste cooking oil biodiesel as fuel enhancer on diesel engine performance and emission characteristics," *Sustainable Energy Technologies and Assessments,* vol. 52, p. 102291, 2022/08/01/ 2022.

[75] A. E. Kabeel, M. Elkelawy, H. A. E. Bastawissi, and A. M. Elbanna, "An experimental and theoretical study on particles-in-air behavior characterization at different particles loading and turbulence modulation," *Alexandria Engineering Journal,* vol. 58, pp. 451-465, 2019/06/01/ 2019.

[76] M. Elkelawy, A. Kamel, A. Abou-elyazied, and S. M. El-malla, "Experimental investigation of the effects of using biofuel blends with conventional diesel on the performance, combustion, and emission characteristics of an industrial burner," *Egyptian Sugar Journal,* vol. 19, pp. 44-59, 2022.

[77] M. El-kadi, M. Hosien, M. Younes, and I. Teaima, "THE EFFECT OF SOLID-LIQUID MIXTURE ON CAVITATION CHARACTERISTICS OF A CENTRIFUGAL PUMP," *ERJ. Engineering Research Journal,* vol. 32, pp. 511-520, 2009.

[78] J. Herbich and R. Cooper, "II." The Effect of Solid-Water Mixtures on Cavitation Characteristics of Dredge Pumps,"" in *Proceedings Fourth World Dredging Conference, New Orleans, LA*, 1971.

[79] G. Addie, K. Wilson, and A. Sellgren, "Suction performance of centrifugal pumps and its effect on cost of slurry transport," in *BHR GROUP CONFERENCE SERIES PUBLICATION*, 1999, pp. 515-526.

[80] S. A EL-Agouz, H. A. E. Mohamed, and E. Nossir, "Experimental Investigation on a Slurry Pump at Different Operating Parameters," *Journal of Engineering Research,* vol. 4, pp. 81-87, 2020.

[81] V. Aleksandrov and C. Menshikov, "Quotient of slurry pump technical state," *Natural and Engineering Sciences,* vol. 4, pp. 66-71, 2014.

[82] S. F. Abd El Fattah, M. F. Ezzat, M. A. Mourad, M. Elkelawy, and I. M. Youssef, "Experimental Investigation of the Performance and Exhaust Emissions of a Spark-Ignition Engine Operating with Different Proportional Blends of Gasoline and Water Ammonia Solution," *Journal of Engineering Research,* vol. 5, pp. 38-45, 2022.

[83] M. Elkelawy, Z. Yu-Sheng, H. El-Din, Y. Jing-Zhou, A. El Zahaby, and E. El Shenawy, "Experimental Study on Flash Boiling and Micro-Explosion of Emulsified Diesel Fuel Spray Droplets by Shadowgraph Technology," *Transactions of CSICE,* vol. 27, pp. 306-308, 2009.

[84] M. Elkelawy, E. S. A. El Shenawy, H. A. Bastawissi, and M. M. Shams. (2023, Impact of Carbon Nanotubes and Graphene Oxide Nanomaterials on the Performance and Emissions of Diesel Engine Fueled with Diesel/Biodiesel Blend. *Processes 11(11)*.

[85] M. Elkelawy, H. Alm ElDin Mohamad, M. Samadony, and A. S. Abdalhadi, "Impact of Utilizing a Diesel/Ammonia Hydroxide Dual Fuel on Diesel Engines Performance and Emissions Characteristics," *Journal of Engineering Research,* vol. 7, pp. 262-271, 2023.

[86] A. E. Kabeel, M. Elkelawy, H. A.-E. Mohamad, A. M. Elbanna, H. Panchal, M. Suresh*, et al.*, "The influences of loading ratios and conveying velocity on gas-solid two phase flow characteristics: a comprehensive experimental CFD-DEM study," *International Journal of Ambient Energy,* vol. 43, pp. 2714-2726, 2022/12/31 2022.

[87] H. A.-E. Bastawissi and M. Elkelawy, "Investigation of the Flow Pattern inside a Diesel Engine Injection Nozzle to Determine the Relationship between Various Flow Parameters and the Occurrence of Cavitation," *Engineering,* vol. Vol.06No.13, p. 13, 2014.

[88] H. Alm El-Din, M. Elkelawy, and A. E. Kabeel, "Study of combustion behaviors for dimethyl ether asan alternative fuel using CFD with detailed chemical kinetics," *Alexandria Engineering Journal,* vol. 56, pp. 709-719, 2017/12/01/ 2017.