Isı Bilimi ve Tekniği Dergisi,43, 1, 119-134, 2023
J. of Thermal Science and Technology

ISSN 1300-3615
https://doi.org/10.47480/isibted.1290753

THE PERFORMANCE OF WATER JET PUMPS AND THEIR APPLICATION IN SLURRY TRANSPORTATION

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(Geliş Tarihi: 14.06.2022, Kabul Tarihi: 26.04.2023)

Abstract: This present work is focused firstly on an experimental investigation for the optimum design of water jet pumps to be used in the hydrotransport of solid particles through pipeline systems. Experiments were conducted in a closed test loop using five types of jet pumps with various dimensions of the driving nozzle, suction nozzle, mixing chamber, and diffuser employing water as driving and suction fluid. The efficiency of each water jet pump element was analyzed and interpretations of results related to each water jet pump were made about the parts to be considered in the optimum design of a water jet pump. From the experimental results, the water jet pump having the optimum mixing chamber, suction nozzle, driving nozzle location, and cross-sectional dimensions produced a maximum efficiency of about 33%. In the second part of the study, the solid particle carrying capacity of water jet pumps in a pipeline system was studied under saltation, moving bed, and heterogeneous flow regimes by introducing seven different types of solid particles having various concentrations into the closed test loop. The effect of jet pumps on separating solid particles from flow in a region was investigated. A curved form of a by-pass system called the 'flow division unit' was added to the main pipeline system and through the flow division unit, then most of the solid particles in the flow were forced to flow towards the suction pipe of the jet pump. As a result of this, only water with very small particle concentrations passed through the centrifugal pumps, and in this way, the wear risk of the centrifugal pump was reduced considerably.
Keywords: water jet pump, pipeline system, slurry transportation, centrifugal pump wear.

SU JET POMPALARININ PERFORMANSI VE KATI-SIVI KARIŞIM TAŞIMACILIĞINDA UYGULANMASI

Özet: Bu çalışma öncelikle, katı parçacıkların boru hattı sistemleri aracılığıyla suyla taşınımında kullanılacak su jeti pompalarının optimum tasarımı için deneysel bir araştırmaya odaklanmıştır. Deneyler, hem tahrik hem de emme sıvısı olarak su kullanan tahrik nozulu, emme nozulu, karıştırma haznesi ve difüzörün çeşitli boyutlarına sahip beş tip jet pompası kullanılarak kapalı bir test döngüsünde gerçekleştirildi. Her bir su jeti pompası elemanının verimliliği analiz edilmiş ve her bir su jeti pompasına ilişkin sonuçların, bir su jeti pompasının optimum tasarımında dikkate alınması gereken parçalar hakkında yorumları yapılmıştır. Deneysel sonuçlardan, optimum karıştırma haznesi, emme nozulu, tahrik nozulu konumu ve kesit boyutlarına sahip su jet pompası, yaklaşık %33'lük maksimum verimle üretilmiştir. Çalışmanın ikinci bölümünde, bir boru hattı sistemindeki su jeti pompalarının katı madde taşıma kapasitesi, çeşitli konsantrasyonlara sahip yedi farklı katı maddenin kapalı test döngüsüne sokularak sıçramalı, hareketli yatak ve heterojen akış rejimleri altında incelenmiştir. Jet pompasının bir bölgedeki katı partikülleri akıştan ayırmadaki etkisi araştırıldı. Ana boru hattı sistemine 'akış bölme ünitesi' adı verilen kavisli bir by-pass sistemi eklendi ve akış bölme ünitesi aracılığıyla, akıştaki katı parçacıkların çoğu jet pompasının emme borusuna doğru akmaya zorlandı. Böylece santrifüj pompalardan sadece çok küçük partikül konsantrasyonlarına sahip su geçmiş ve bu şekilde santrifüj pompanın aşınma riski önemli ölçüde azaltılmıştır.
Anahtar Kelimler: su jeti pompası, boru hattı sistemi, bulamaç nakliyesi, santrifüj pompa aşınması.

NOMENCLATURE

Abbreviations

A	Area
C	Concentration
D	Diameter (or size)
E	Total head
g	Gravitational constant
L	Length
M	Non-dimensional flow ratio
m	Mass flux
N	Non-dimensional head ratio
Q	Discharge
V	Velocity
t	Time
x	Distance

η	Efficiency
θ	Angle
ρ	Density of the fluid
γ	Specific weight of the fluid

Subscripts

d	driving line
ds	diffuser
in	into the system
mix	mixture
mc	mixing chamber
n	nozzle, nominal diameter
o,out	out from the system
p	pump
s	suction line
sn	suction nozzle
sp	solid particle
w	water, weight

INTRODUCTION

The flow of slurries in pipes takes place in a variety of industrial applications due to its economic importance. Mixtures of liquids, mainly water and solids such as sand, gravel, clay, coal, various ores, plastics, etc., are transported over short and long distances. While transporting solid-liquid mixtures, a number of flow regimes can be encountered as the flow velocity increases. Detailed information on those of the flow regimes of solid-liquid mixtures in closed-conduits was extensively given by Graf (1971) and ASCE (1975). The transport of relatively coarse particles has been limited to short distances because of high necessary operating velocities resulting in extensive wear in the pipeline system and excess energy consumption. When designing a solid-transporting pipeline system using centrifugal pumps, it is necessary to know the effect of solids on the performance of the pumps. For example, even a small deviation in pump speed from a predetermined mean value over a long period of time can be very expensive due to increased wear in the system. Frequent pump disassembly and installation not only consumes much time, but the frequent replacement of the flow passage components is very expensive also (Peng et al. 2020). In addition, the flow of solids through the pump causes additional hydraulic losses due to the relative movement of coarse particles or the viscous effects of high concentration of solid particles due to the different densities of solids and liquids. As the concentration of solid particle increases, the damage because of abrasion becomes more serious. In order to avoid these problems, somehow the amount of solid particles which will pass directly through pumps should be reduced. This situation can be achieved if the combination of a centrifugal pump and a jet pump is used in the system as shown in Figure 1.

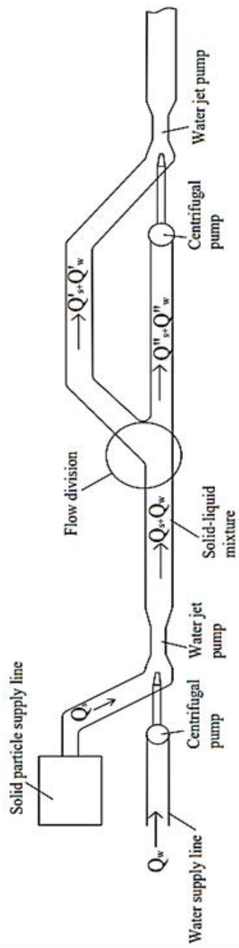


Figure 1. A general layout of a solid-liquid carrying pipeline system with the combination of bypass and water jet pump

The jet pump operates without moving parts and consists of four main elements; i.e. driving nozzle, suction nozzle, mixing chamber, and diffuser. Because the jet pumps do not contain any moving parts, they are less affected by the abrasion. Beside this obvious advantage, its simple design, easy maintenance, simple operation, and applicability to high-density fluids are some of the other significant benefits of jet pumps. Jet pumps can be made of great variety of materials and they can be used in various fields like fluid jet mixers, jet heaters, or steam jet compressor depending on the flow mediums used. If the driving and suction fluids are water, the jet pump is named as "water jet pump (WJP)" which is the main concern of this paper. Water jet pumps are used in many civil engineering practices like deep-well pumping and dredging.

Water jet pump was first used by Thomson after the development of the two streams mixing theory by Rankine (Reddy and Kar, 1968). In the later works, the researchers tried to obtain the geometry of a water jet pump for which the maximum performance would be achieved. The past research showed that the efficiencies of jet pumps tested were varied in the range of 20.8-42 % at flow ratios M, which is the ratio of suction flowrate to driving flowrate, of 0.2-1.2 (e.g. Muller (1964), Reddy and Kar (1968), Cairns and Na (1969), Cunningham (1995), Wang and Wypych (1995), El-Sawaf (1999), Winoto et al. (2000), Neto (2011), Xiao and Long (2015), Yapıcı and Aldaş (2013), Sheha et al. (2018), Zhao and Sakuragi (2018)).

In a water jet pump, the pumping action is performed by the transfer of energy from a high velocity jet to one of low velocity suction fluid. In case of solid-liquid flow in a pipeline, a typical jet pump as shown in Fig. 2 is operated by a pump producing a driving jet of clean liquid through a nozzle which will entrain to the solid-liquid mixture. The momentum exchange between the driving jet and entrained mixture occurs within a mixing chamber and the high kinetic energy is then converted into pressure energy through a diffuser.

The main contribution of this study in slurry transporting systems is to reduce the ratio of solid particles passing through the centrifugal pump by using water jet pumps with a flow separation unit and to prevent the centrifugal pump wear problem. To the knowledge of the authors, there is no study using these two elements (water jet pump and flow separation unit) together. In the present experimental work, a water jet pump and a flow division unit have been used in conjunction with a centrifugal pump in order to avoid solid particles passing through the centrifugal pump in a pipeline system transporting solid-liquid mixture. The efficiencies of the water jet pumps tested were determined and the amounts of solid particles passing through the centrifugal pump were measured for different solid particles having various concentrations and for different flow regimes; namely in saltation, moving bed, and heterogeneous regimes. Seven different types of solid particles, five types of suction nozzles, driving nozzles, and mixing chambers were examined in the course of this study.

THEORETICAL BACKGROUND

Water Jet Pump

The performance of a water jet pump is commonly expressed in terms of its efficiency η, which is simply defined as the ratio of power output to power input of the system (Fig. 2),

$$\eta = \frac{(Power)_{out}}{(Power)_{in}} = \frac{Q_s(E_d - E_s)}{Q_p(E_p - E_d)} = MN \qquad (1)$$

in which, $(Power)_{in} = \gamma_w Q_p(E_p - E_d)$, $(Power)_{out} = \gamma_w Q_s(E_d - E_s)$, γ_w is the specific weight of water, Q_s is the suction fluid flow rate; Q_p is the driving fluid flow rate; E_d is the total head at the exit of the diffuser (Section (d)-(d)); E_s is the total head of the suction liquid (Section (s-s)); E_p is the total head of driving liquid (Section (p-p)); and the non-dimensional volume flow rate, and the non-dimensional head ratio, are defined as $M = Q_s/Q_p$, and $N = (E_d - E_s)/(E_p - E_d)$, respectively. It should be noted that (1) is non-dimensional and includes the overall losses encountered in the water jet pump.

In the experimental analysis of a water jet pump, in order to obtain the highest possible efficiency one should consider geometrical parameters of each element of the jet pump, that is, different values for lengths, diameters and angles made with respect to each other have to be investigated. It is obvious that making all these changes and tests will be time consuming and also very costly. The experiments were conducted with varying dimensions of driving nozzle, mixing chamber, suction nozzle, and diffuser. The minimum energy just before the jet pump prevails at Section (s)-(s). The maximum total head to which the suction fluid will be raised, which can also be named as the pump lifting height, is equal to $(E_d - E_s)$. The power output from the pump is determined by $\gamma_w Q_s(E_d - E_s)$ whose division by $\gamma_w Q_p(E_p - E_d)$ produces the pump efficiency given in (1).

Slurry Flow with Water Jet Pumps

Solid-liquid mixtures having high solid concentrations have strong influences on pump head, efficiency, and pump power consumption. These influences vary with material types and different particle sizes. Ni et al. (1999) reported that when volumetric concentration C_v was equal to 42%, the centrifugal pump efficiency could drop almost 60% in the coarse sand slurry as compared to the efficiency that of only water. They also pointed out that power requirement increases with relative density of the slurry.

The function of a water jet pump in the solid transporting pipeline system is mainly to avoid the particles from passing through the centrifugal pump. As it has been stated before, the abrasive action of the solid particles gives damages to rotating parts of the centrifugal pumps as well as to pipes. Since centrifugal pumps are the most important elements of a solid transporting pipeline system, a special attention should be given and ways of preventing them from wear should be searched. Noon and Kim (2016) numerically investigated erosion prevention caused by the lime slurry and its effects on head and efficiency losses in centrifugal pumps. They found that erosion loss increased with impact velocity, concentration by weight, and diameter of solid particles. Tarodiya and Gandhi (2019) focused on investigating the relationship between the abrasive wear profile of the pump body and the simulated flow field experimentally and numerically to determine the influence of the dominant factors affecting the wear of the pump bodies under different operating conditions. Li et al. (2020) numerically simulated solid-liquid flow in a centrifugal pump using CFD-discrete element method coupling. They stated that with the increase in the particle concentration, the head and efficiency of the centrifugal pump dropped significantly, and the wear rate of the centrifugal pump wall was closely related to the particle concentration.

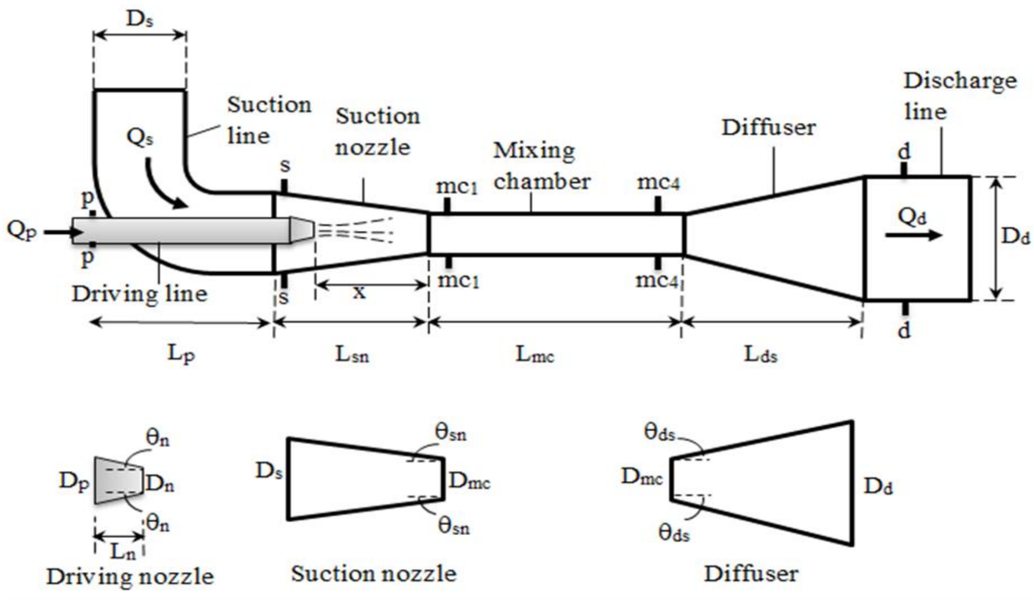


Figure 2. A typical water jet pump with its elements

In this study, a jet pump, a centrifugal pump, and a flow division unit were used in a laboratory closed test loop to minimize the amount of solids, which could pass through the centrifugal pump as seen in Figs. 3 and 4. The pipeline system at the by-pass was divided into two branches (named as "Flow Division Unit") before the centrifugal pump. While one of the branches (outer) was directly connected to the centrifugal pump, the second one (inner) was making a curvature and forming a by-pass. It is known that when a solid-liquid mixture flow approaches a bend of either a pipe or an open channel, the fluid particles and solid particles at the bottom levels of the flow have a tendency to move towards the inner side of the bend due to the effect of centrifugal forces that cause secondary currents at the cross section (Graf, 1971; ASCE, 1975, Julien, 2002). Referring to this principle it was shown that more solid particle discharge of the system was passing through the inner branch and then combining with the rest of the solid particle discharge after the jet pump unit.

In addition to the emphasized advantage of the by-pass system, there is another important point that should not be forgotten is the additional energy losses. When a pipeline system with by-passes and jet pumps (as seen Fig. 1) are to be preferred to the one which is free of by-passes and having only centrifugal pumps at certain locations, some additional energy losses occur in the whole system due to the by-passes and jet pumps. These undesired losses can be minimized by using optimum design criteria to be obtained from theoretical and experimental studies for by-passes and jet pumps.

The theoretical work to be done here is valid for the control volume applied to the system where all experiments were performed. The equations used in the determination of solid particle concentrations passing though the suction line and pump were derived from the basic law of conservation of mass applied to the pipeline system shown in Fig. 3. In the case of having water as the fluid being transported, the mass flux entering the system through the driving line m_p, is equal to the mass flux leaving the system m_o, because the rate of change of mass of water inside the system is zero. The mass flux in the discharge line, md, is equal to the summation of the mass fluxes in the suction line m_s, and that leaving the system m_o, or entering the system m_p.

Introducing solid particles of known weight into the system changes the calculation procedure to a degree. Since the driving fluid in this study is always water, then the mass fluxes of the fluid entering and leaving the system are not same. Some fraction of the solid particles introduced escaped out as a function of time; therefore, the rate of change of mass of solid-water mixture inside the system is not zero.

Applying the law of conservation of mass for the pipeline system, one can write,

$$\frac{\Delta m_d}{\Delta t} + m_0 - m_p = 0 \quad (2)$$

where $\frac{\Delta m_d}{\Delta t}$ is the rate of change of mass of solid-water mixture inside the control volume, m_o is the mass flux flowing out of control volume and m_p is the mass flux flowing inside the control volume. From experiments conducted, values of m_o and m_p were determined and by means of (2) the magnitude of $\frac{\Delta m_d}{\Delta t}$ was calculated. However, it was seen that this amount was negligible compared to other terms. Then (2) takes the form of,

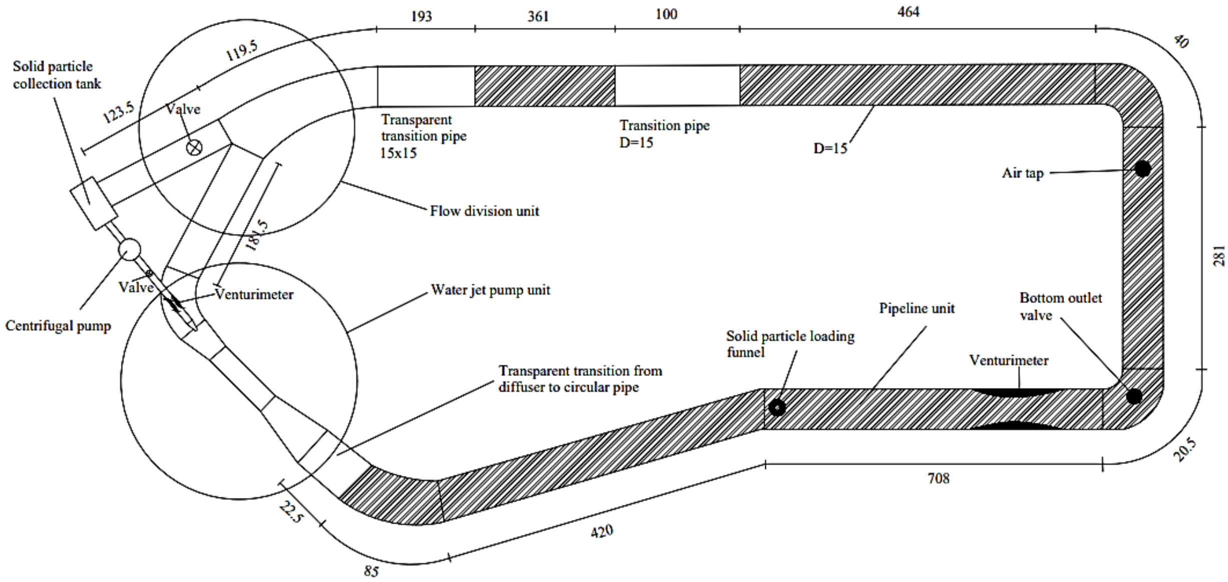


Figure 3. Experimental set-up used in the study

$$m_o \cong m_p \quad (3)$$

Expressing m_o and m_p as,

$$m_o = (\rho_{mix} Q_{mix})_o \quad (4)$$

and,

$$m_p = (\rho_w Q_w)_p \quad (5)$$

where ρ is the density, Q is the discharge and the subscripts "*mix*" and "*w*" refer to mixture and water, respectively. Substituting (4) and (5) into (3),

$$(\rho_{mix} Q_{mix})_o = (\rho_w Q_w)_p \quad (6)$$

The results of experiments carried out with different solid particles revealed that $(\rho_{mix})_o \cong (\rho_w)_p$ from which the following relation can be written,

$$(Q_{mix})_o \cong (Q_w)_p \quad (7)$$

The total dry weight of the solid-water mixture Wmix escaped out from the system during the time period of Δt can be determined as,

$$(W_{mix})_o = (\gamma_{mix} Q_{mix} \Delta t) = \gamma_w Q_p \Delta t \quad (8)$$

where γ is the unit weight. The weight concentration of the solid particles, C, flowing out of system, which is actually the concentration of the solid particle which will pass through the centrifugal pump, is computed from the equation below,

$$C_o = C_p = \frac{(W_{sp})_o}{(W_{mix})_o} = \frac{(W_{sp})_o}{\gamma_w Q_p \Delta t} \quad (9)$$

where $(W_{sp})_o$ is the total weight of the solid particle flows out of the system during the time period of Δt and subscript "sp" refers to solid particle dry weight.

In a similar way, the concentration of the solid particles passing through the suction line can be determined as

$$C_s = \frac{\gamma_{sp} Q_s}{(\gamma_{mix} W_{mix})_s} \quad (10)$$

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

Test facility used in this study was designed and assembled at the Hydraulics Laboratory of Middle East Technical University. Following the construction of the test set-up, several research activities were conducted on hydraulic transport of solids in pipes (i.e. İnci (1987), Kökpınar (1990), and Kökpınar and Göğüş (2001)).

Figure 3 shows the general layout and dimensions of experiment set-up. The whole system horizontally mounted on steel supports of height 0.60 m above the laboratory bottom level can be analyzed into three parts; pipeline unit, flow division unit, and water jet pump unit. The pipeline unit consisted of a steel pipe 0.15 m in diameter and 26 m long.

As it is seen in Fig. 3, the pipeline unit started following the water jet pump unit and continued up to the transparent transition pipe of square cross-section, with dimensions of 0.15 cm x 0.15 cm. The transparent pipe which was 1.0 m long and 0.15 m in diameter located close to the downstream end of the pipeline unit was used as an observation pipe during the experiments. Solid particles were introduced into the system by means of a funnel. The total flow discharge passing through the pipeline unit was measured by a venturimeter of 0.1 m in throat diameter. The bottom outlet valve was used to unload the system after finishing each experiment.

The sketch showing geometrical details of flow division unit and its photographs before and after installation are seen in Fig. 4. This unit, which was at the downstream of the transparent transition pipe of square cross-section with dimensions of 0.15x0.15 m, was divided into two branches. The first branch (outer branch), which works as outlet conduit, has a rectangular cross-section of width and height 0.10 m and 0.1125 m, respectively. At the end of this pipe, a valve was located for the adjustment of the flowrate leaving the system. The second branch (inner branch) of the flow division unit with a different radius of curvature than the first one but has a rectangular cross-section with the same dimensions of the first branch works as a suction conduit for the jet pump unit. Just at the downstream of the pipe, a sliding gate was constructed to divert the flow when cleaning up the system from settled solid particles. A 90^o-bend of constant cross-section area connects the suction pipe to the water jet pump. In all experiments the dimensions of the elements forming the flow division unit were kept constant.

The water jet pump unit was composed of a suction nozzle, a mixing chamber, a diffuser, and a driving line with a driving nozzle. The length and diameter of the driving line and the suction line, which connected the suction chamber to the flow division unit, were kept constant in all experiments. The flow rate of the driving fluid was measured by a venturimeter of throat diameter 0.028m. Five types of jet pumps with different dimensions were manufactured and tested with varying driving nozzle diameters as seen from Table 1.

Seven types of solid particles of different properties (fine and coarse tuffs, blue and black granular plastics, coal, fine sand, and coarse aggregate) were used in the solid-liquid transportation experiments. Table 2 shows the characteristics of solid particles used in the experiments. The specific gravities of the solid particles were varying in the range of 1.05-2.60. The granular plastic particles had uniform dimensions with 1.5x2.0x2.0 mm. Particle size distribution of the non-uniform particles are given in Fig. 5.

For several values of driving line water discharge Q_p, starting from the minimum up to the maximum obtainable ones, the experiments were carried out and static pressure head in the piezometer tubes on manometers were recorded. The presence of turbulence caused fluctuations in water levels of piezometer tubes and required special attention to obtain the water levels in each piezometer tube under the same hydraulic condition. The maximum height of the variation observed in the measurements of water levels in piezometer tubes was about 0.015 m causing $\pm$ 3% error in the measured pressure head. In addition, the measurement of the mixture discharge involved using a Venturi meter positioned in the pipeline unit. However, it was found that during high flow rates, variations in the water manometers linked to the Venturi meter could lead to a potential 2% discrepancy in the discharge measurement, thereby generating an equivalent mistake in the flow velocity. In order to achieve accurate experimental values for each parameter (such as pressure, discharge, solid weight, etc.), the tests were conducted multiple times using the same amount of particles, with a minimum of two or three repetitions.

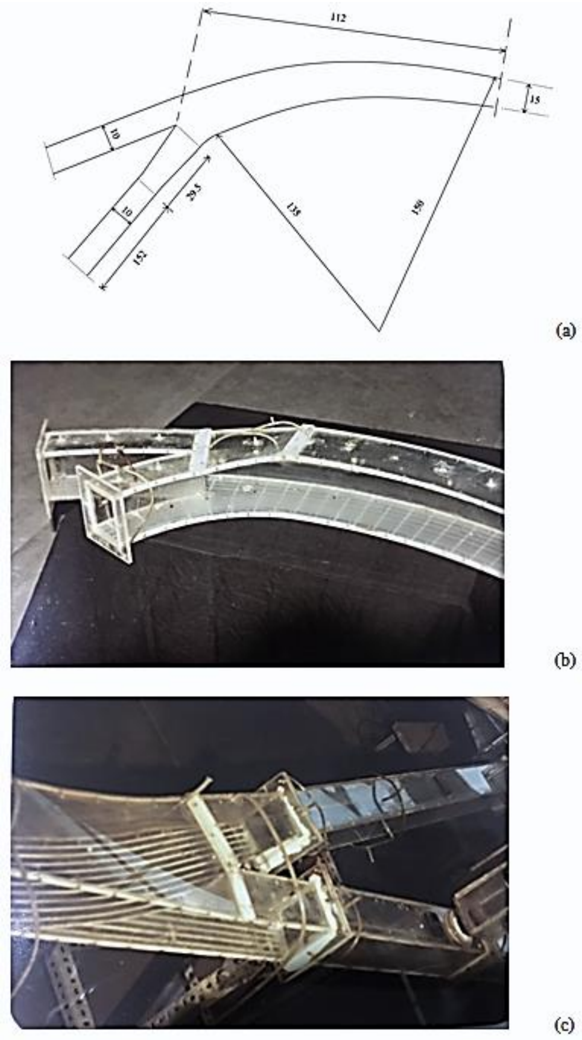


Figure 4. Flow Division Unit a) geometrical details, b) photo before installation (view from inner branch), and c) after installation (view from outer branch)

After completing the experiments on water jet pumps to obtain highest efficiency geometry, following experiments were conducted to investigate the effect of a jet pump on solid particle transport capacity of the system and to observe the performance of the flow division unit on the separation of solid particles. Seven different types of solid particles with various specific gravity values were used as test materials. For the jet pump and driving nozzle, a flowrate was set in the system by adjusting valves on driving line and outlet valve. Then, the experiments for a given type and weight of the solid particle was carried out by slowly introducing the solid particles through the loading funnel. The solid particles were carried away through the pipe under the influence of flow in the pipe. The movement of the solid particles was observed through the transparent pipes on the system to define the regime of solid transport. Since the discharge of the driving line was kept initially at a low value most of the time solid particles settled in the pipe forming discrete steps in rectangular shape with a gentle upstream but steep downstream slopes. Only the grains on the top of these steps moved along the flow direction and settled in front of the downstream slopes, after travelling relatively short distances. Accumulations of the solid particles especially along the inner branch of the flow division unit and at the suction line were always observed. While the flow occurring in the system, a small fraction of the solid particles was withdrawn through the flow outlet pipe, but collected in a collection tank. After the solid particles were observed at almost any section of the whole system, not necessarily in moving form, the solid particles collected in the collection tank were added to the flow of the system. Then, for a period of about 3 minutes, the flow of solid-water mixture was observed and the particles flowing out of the system were collected. When the period was completed, the solid particles collected in the collection tank were weighed and recorded. This measurement procedure was repeated for the other system discharges obtained from increasing driving line discharge Q_p and necessary observations and data were recorded or collected accordingly. Figure 6 presents the process chart of the experimental program.

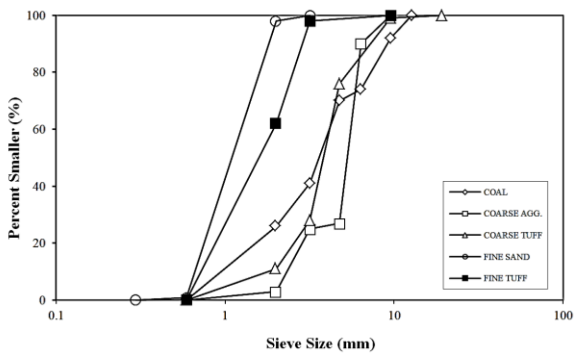


Figure 5. Grain size distribution of non-uniform solid materials used in the experiments

INTERPRETATION OF RESULTS

Water Jet Pump Efficiency

Effect of driving nozzle diameter

Figures 7a-7c have been created to compare and analyze the performance of each type of water jet pump (WJP) used in the experiments. The comparison is based on the relationship between the input power $(Power)_{in}$ and the output power $(Power)_{out}$, with the driving nozzle diameter, D_n, used as a parameter for a given mixing chamber dimension. The first three WJPs (WJP-1 to WJP-3), which have different mixing chamber and suction nozzle geometries as outlined in Table 1, were tested to determine the effect of the driving nozzle diameter D_n on the overall efficiency of the WJPs. It is worth noting that in all three WJP tests, as shown in Figure 2, the driving nozzle was located at the entrance section of the suction nozzle, with a value of $x = L_{sn}$.

Table 1. Geometric characteristics of water jet pump elements used in the experiments (lengths in cm and angles in degree)

Water Jet Pump	Driving line		Driving nozzle		Suction line	Suction nozzle			Mixing chamber		Diffuser		Discharge line
	D_p	L_p	D_n	L_n	A_s	θ_{sn}	L_{sn}	x	A_{mc}	L_{mc}	θ_{ds}	L_{ds}	D_d
WJP 1.1			2.0	2.5									
WJP 1.2	5	50	3.0	2.5	10x11.25	7.12	20	20	5x5	33	5.95	48	15
WJP 1.3			4.0	2.0									
WJP 2.1			2.0	2.5									
WJP 2.2			3.0	2.5									
WJP 2.3	5	50	4.0	2.0	10x11.25	4.29	20	20	7x7	33	4.75	48	15
WJP 2.4			4.5	2.0									
WJP 2.5			5.0	2.0									
WJP 3.1			3.0	2.5									
WJP 3.2	5	50	4.0	2.0	10x11.25	1.14	25	25	9x9	26	3.43	50	15
WJP 3.3			4.5	2.0									
WJP 3.4			5.0	2.0									
WJP 4.1								25					
WJP 4.2	5	50	4.5	2.0	10x11.25	1.14	25	4.5	9x9	65.5	3.43	50	15
WJP 4.3								13					
WJP 5.1						2.29	12.5	5.5					
WJP 5.2	5	50	4.5	2.0	10x11.25			6.1	9x9	78	3.43	50	15
WJP 5.3								10.5					

Table 2. Characteristics of solid particles used in the experiments

Solid Particle	Specific weight γ (gr/cm^3)	Median diameter d_{50} (mm)	Nominal diameter d_n (mm)
Coarse tuff	1.05	3.89	
Blue plastics	1.20		2.25
Fine Tuff	1.31	1.65	
Black plastics	1.35		2.25
Coal	1.74	3.70	
Coarse gravel	2.55	5.34	
Fine sand	2.60	1.09	

During the experiments on WJP-1, which had a mixing chamber diameter of 5 cm, three different driving nozzle diameters were tested: D_n =2 cm, D_n =3 cm, and D_n =4.5 cm, labeled as WJP 1.1, WJP 1.2, and WJP 1.3, respectively. However, despite the input power $(Power)_{in}$ ranging up to 1400 watts, the maximum $(Power)_{out}$ achieved was only about 15.6 watts. This resulted in a low efficiency for the jet pump, determined by dividing $(Power)_{out}$ by $(Power)_{in}$. Out of the driving nozzle diameters tested, D_n =4.5 cm was the worst performer in terms of system efficiency. For a given $(Power)_{in}$ value, the other driving nozzle diameters yielded nearly the same amount of power.

In the WJP-2 experiments with a mixing chamber diameter of 7 cm, the slopes of the lines connecting the same series of data points were found to be steeper than those in Figure 7a. Within the range of experiments conducted, D_n =4.5 cm (WJP 2.4), followed by D_n =3.0 cm (WJP 2.2) and D_n =4.0 cm (WJP 2.3), produced the maximum $(Power)_{out}$ for a given $(Power)_{in}$.

In the WJP-3 experiments with a mixing chamber diameter of 9 cm, the data points for D_n =4.0 cm (WJP 3.2) and D_n =4.5 cm (WJP 3.3) were almost coinciding and produced the highest values of $(Power)_{out}$ for the given $(Power)_{in}$ values. Comparing Figures 7a, 7b, and 7c, it can be concluded that WJP-3 with a driving nozzle diameter of D_n =4.0 cm or 4.5 cm yielded the maximum pump efficiency of about η=0.27.

For the next two water jet pumps, i.e. WJP-4 and WJP-5, the driving nozzle diameter and mixing chamber cross-section dimensions were fixed at D_n =4.5 cm and D_{mc}=9 cm, respectively, in order to analyze the effects of driving nozzle location, suction nozzle length, and mixing chamber length on the overall water jet pump efficiency. The corresponding driving nozzle to mixing chamber cross-section area ratio was A_n/A_{mc}=0.198 for the case of D_n=4.5 cm and D_{mc}=9 cm.

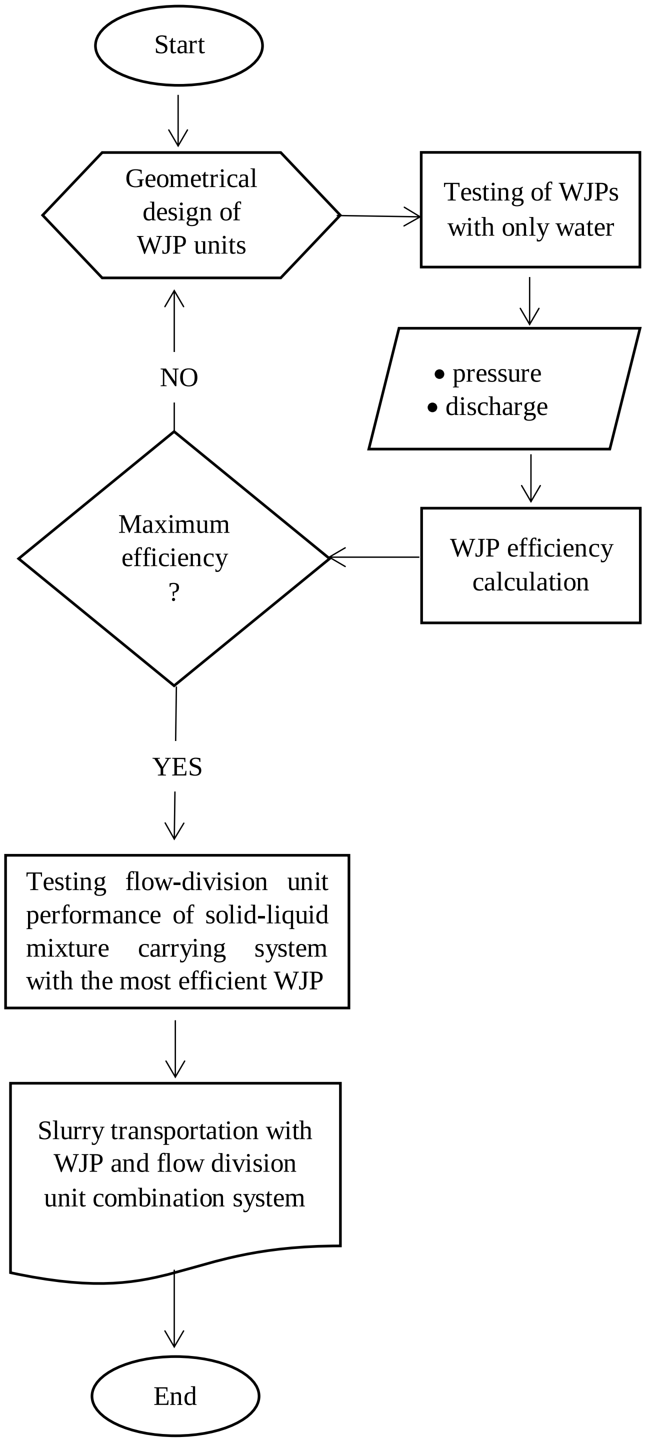


Figure 6. Process chart of the experimental program

Effect of driving nozzle location

In Figure 2, the distance between the entrance of the mixing chamber and the tip of the driving nozzle location (referred to as "*x*") was varied along the suction nozzle to test its effect on the water jet pump's efficiency for each pump in the series of WJP-4 and WJP-5. The efficiency of each case of "*x*" was calculated and normalized with suction nozzle length L_{sn}, i.e., x/L_{sn}. Figure 8 shows $(Power)_{out}$ versus $(Power)_{in}$ to compare the performance or efficiency of each water jet pump as a function of the driving nozzle location. WJP 4.1 has the highest pump efficiency for a given $(Power)_{in}$ with driving nozzle location at x=25 cm (x/L_{sn} =1.0). However, the efficiencies of WJP 4.2 and WJP 4.3 are not significantly different from that of WJP 4.1. Similarly, WJP 5.3 at x=10.5 cm (x/L_{sn} =0.84) gives the highest $(Power)_{out}$ values for high values of $(Power)_{in}$, which corresponds to an efficiency of η=0.329.

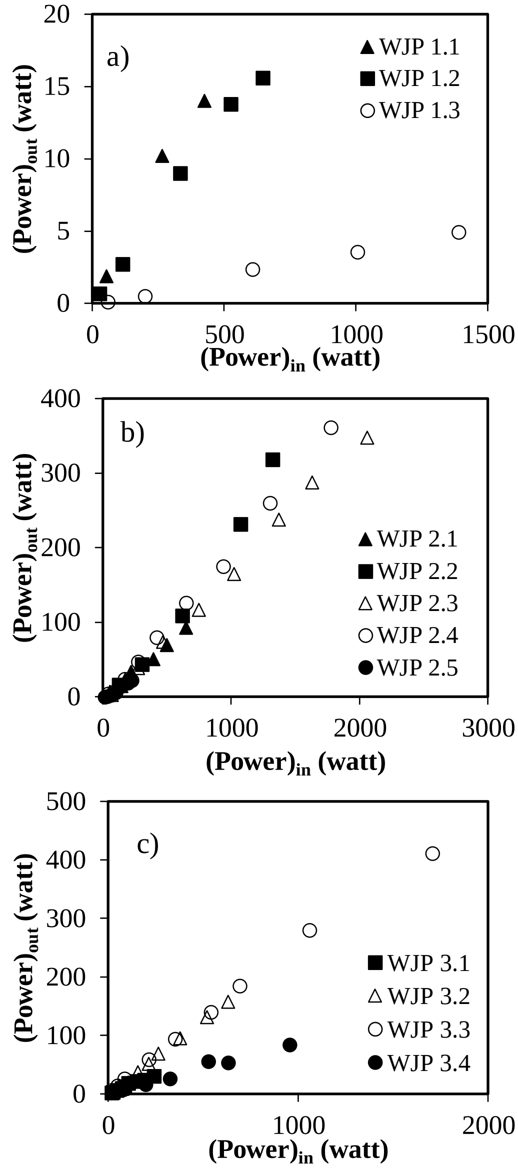


Figure 7. Variation of $(Power)_{in}$ versus $(Power)_{out}$ for various water jet pumps tested as a function of mixing chamber and driving nozzles dimensions for all series of; a) D_{mc}=5 cm for WJP-1, b) D_{mc}=7 cm for WJP-2, c) D_{mc}=9 cm for WJP-3

Relationship between flow ratio (*M*) and water jet pump efficiency (η)

To investigate the impact of suction nozzle length, mixing chamber length, and diffuser angle on the efficiency of water jet pump, Equation (1) was used to calculate the efficiency of each water jet pump. Figure 9 presents the relationship between the flow ratio

(M=Q_s/Q_p) and efficiency (η) of all the water jet pumps tested in the study, along with the geometrical details of each pump provided in Table 1. The M versus η data for all the tested WJPs are shown under the envelope curve in the figure. It can be observed that WJP 5.3 consistently exhibited higher η values than the other tested WJPs. Based on the experimental data presented in Figure 9, the maximum WJP efficiency value of η=0.329 was achieved at a flow ratio of M=1.62. Based on the general trend observed in all experimental data, it can be inferred that the efficiency of the pump first increases and then decreases as M increases, with a maximum value in between. This trend is consistent with previous studies, such as Helios and Asvapoositkul (2021), who achieved a maximum WJP efficiency of η=0.233 at M=0.87, and Schulz and Fasol (Yapıcı and Aldas, 2013), who obtained the maximum jet pump efficiency value of η=0.36 at M=1.4. Yapıcı and Aldas (2013) attributed this trend to the internal structure of flow through the driving and suction lines, which plays a crucial role in the initial increase and subsequent decrease in efficiency with increasing M. The findings of the current study suggest that using a 90° suction line connection to the suction nozzle leads to higher energy losses in the system, ultimately causing a decrease in efficiency. This trend persists even at relatively high efficiency levels, as evidenced by the recorded efficiency of η=0.329 at M=1.62.

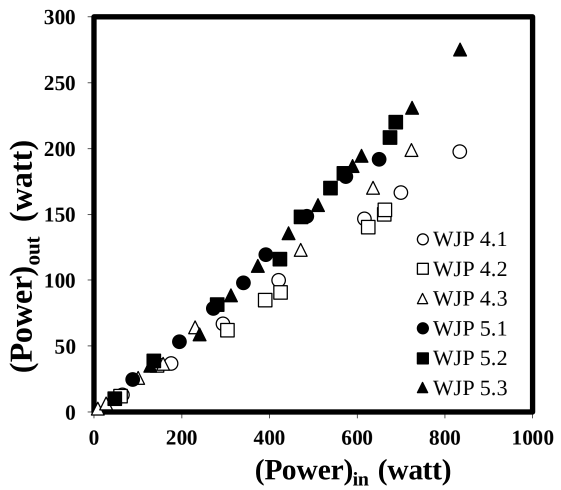


Figure 8. Variation of *(Power)$_{in}$* versus *(Power)$_{out}$* for various water jet pumps tested as a function of driving nozzle location

Effect of Flow Division Unit on Separation of Solid Particles

The studies conducted in this section are based on the analogy of free-surface flows in curved channels. Predicting momentum and sediment transport in curved channels is crucial in river engineering practice. In bends, pressure gradients and centrifugal forces combine to create transverse circulations, also known as secondary flows, spiral flows, or helical flows. These three-dimensional helical flow patterns significantly impact flow behavior and sediment transport in curved channels (Khosronejad et al., 2007), as observed in the scour mechanism in natural curved channels.

In a curved channel, scouring occurs along the outer bank while accumulation takes place along the inner bank due to secondary flows. Secondary flows are closed-circuit flows in a plane perpendicular to the main flow direction. They occur because a fluid element in meandering flow is influenced by two lateral forces. The first one is the pressure gradient in the lateral direction, which has the same value at every point on a vertical section since the pressure distribution is hydrostatic. The second force is the centrifugal force, which decreases as it approaches the bottom because flow velocity is high near the surface and low near the base. Therefore, a fluid element near the surface tends to move to the outside of the curvature, while an element near the bottom moves to the inside. The combination of the secondary flow with the main flow results in a helical flow at the bend. As a result, the secondary flow directed from the outer bank at the base to the inside carries material from the outer bank to the inner bank.

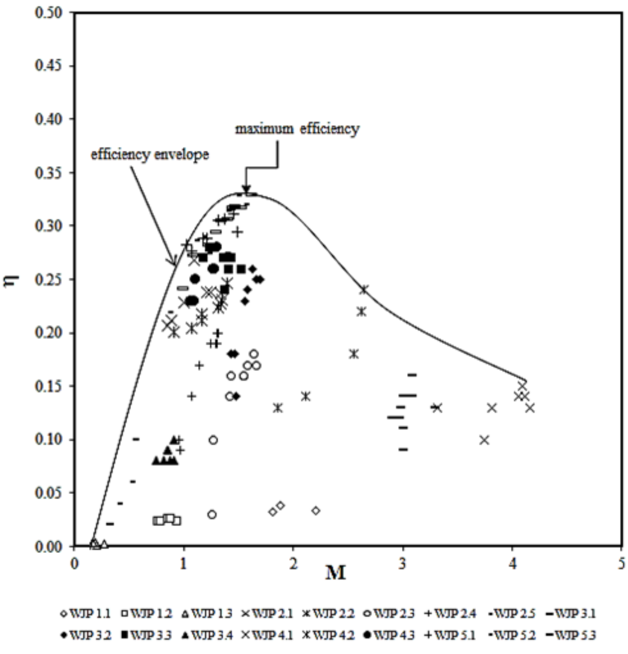


Figure 9. Variation of water jet pump efficiency η with flow ratio M for all water jet pumps tested

Based on the theoretical explanations given above, the experiments conducted in the previous section identified the most efficient type of water jet pump, which was then used to convey seven different types of solid materials through a pipeline system. The aim of this series of experiments was to investigate how the performance of the flow division unit is affected by the particle size and density of the solid materials, as well as the slurry flow regime.

Using the equations developed in the *Slurry flow with water jet pumps* section, the weight concentrations of the solid particles passing through the centrifugal pump $(C_w)_p$ and suction line $(C_w)_s$ were calculated and compared to the concentration of solid material introduced into the system by weight in the discharge line $(C_w)_d$. These concentrations were then plotted and presented in Figures 10a-u. Upon analyzing these figures, it was observed that the concentrations of solid materials passing through the suction line varied between 3.45% and 20.82% for $(C_w)_d$ values ranging from 1.83% to 12.62%, while those passing through the centrifugal pump varied between 0% and 1.49%.

The efficient operation of a flow division unit is greatly influenced by the size of solid particles. For example, when coarse aggregates (Figures 10j,k,l) and fine sand (Figures 10p,q,r) were used in the experiments, the measured concentrations of solids passing through the centrifugal pump, $(C_w)_p$, were found to be in the range of 0.038% - 1.49% and 0% - 0.185%, respectively, when the concentrations of solids in the discharge line, $(C_w)_d$, were between 1.83% - 9.00% for both solid materials. These results indicate that the concentration of coarse particles passing through the centrifugal pump is always higher than that of fine particles, when the solid concentrations in the main pipeline system are the same for the two types of solids with similar densities.

In addition, experiments showed that fine particles tend to move close to each other, especially in the flow division unit, where they follow a path towards the inner branch of the unit, resulting in most of the solid particles returning to the main system, while a small amount goes into the outer branch. The photograph of the movement of fine sand materials along the inner branch in the flow separation unit is shown in Figure 11. These experimental findings are consistent with previous predictions on river bends, such as Allen (1970), Parker and Andrews (1985), Ikeda et al. (1987), Bridge (1976, 1992), and Sun et al. (2001), where coarser grains feel a larger ratio of transverse gravitational force to fluid force than finer grains, leading to lateral sediment size sorting.

In their laboratory tests, Ikeda et al. (1987) concluded that coarser bed materials experience a greater ratio of transverse gravitational force to fluid force than finer grains, making it the primary mechanism for dynamic sorting. They also found that sediment size tends to increase towards the outer bank, resulting in a reduction in lateral bed slope in the outer area of bends. Accordingly, similar to the present study, some of the coarse particles move directly towards the outer branch connected to the centrifugal pump at the beginning of the flow division unit.

Furthermore, the effectiveness of the flow division unit was investigated under different flow regimes of solid-liquid mixtures, which can be classified into four flow regimes (Abulnaga, 2002): a) stationary bed, b) saltation and moving bed, c) heterogeneous mixture with all solids in suspension, and d) homogeneous mixtures with all solids in suspension. In this experimental study, all tests were conducted under the flow regimes of b) and c). While a linear relationship was observed in the moving bed flow regime, the most data scattering was seen in both saltation and heterogeneous flow regimes. Regardless of the material used, data scattering is particularly noticeable at low $(C_w)_d$ values. Thus, it can be concluded that the most stable flow regime is the moving bed flow regime, which is near the critical flow regime.

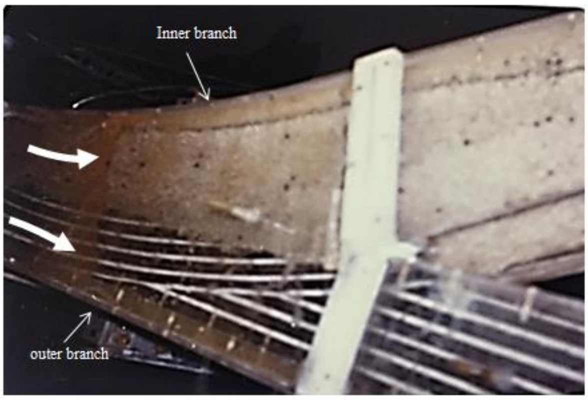


Figure 11. Accumulation of fine sand particles along inner bend of the flow division unit

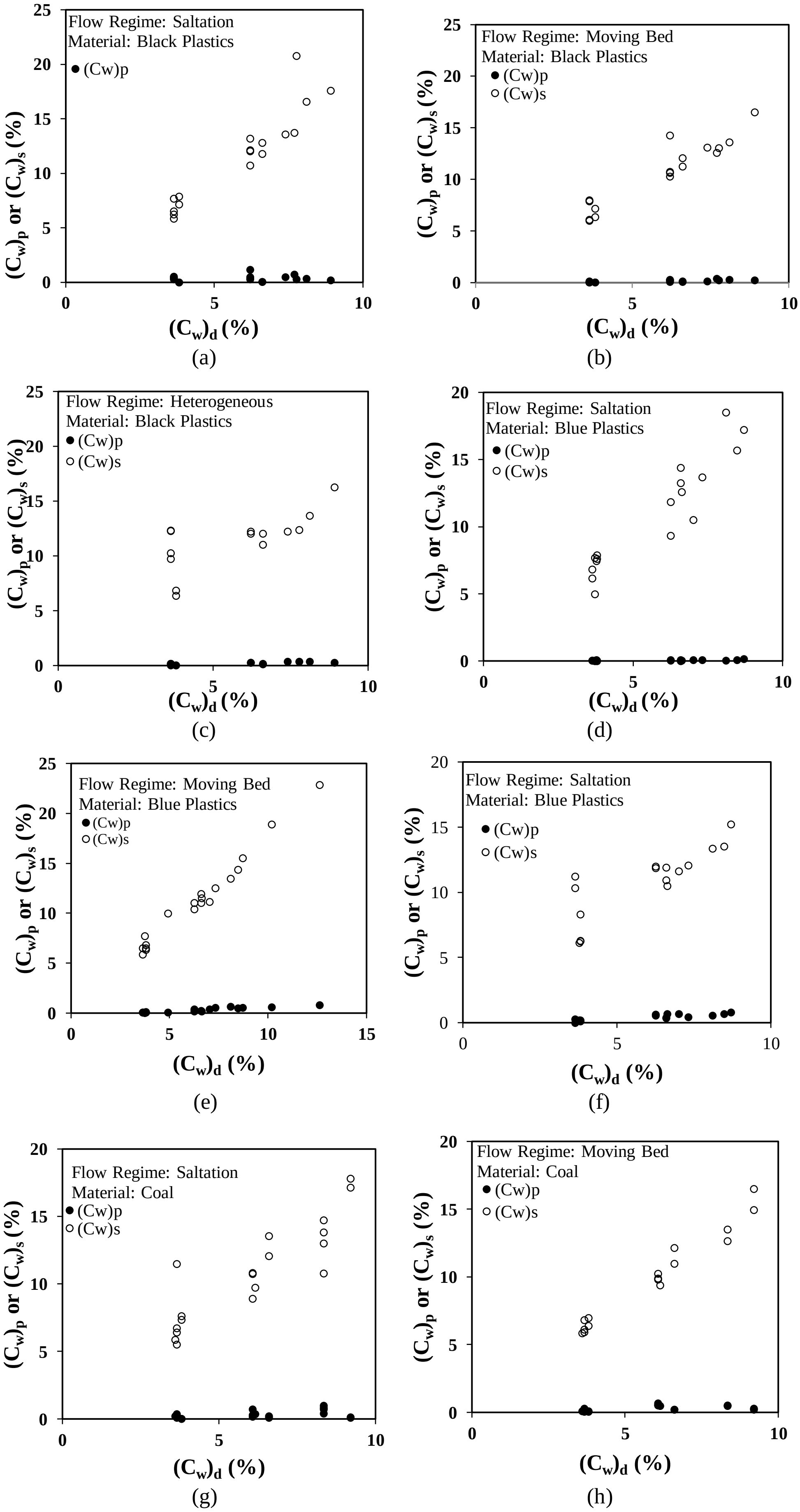


Figure 10. Variation of $(C_w)_p$ or $(C_w)_s$ with $(C_w)_d$ as a function of flow regime and material used

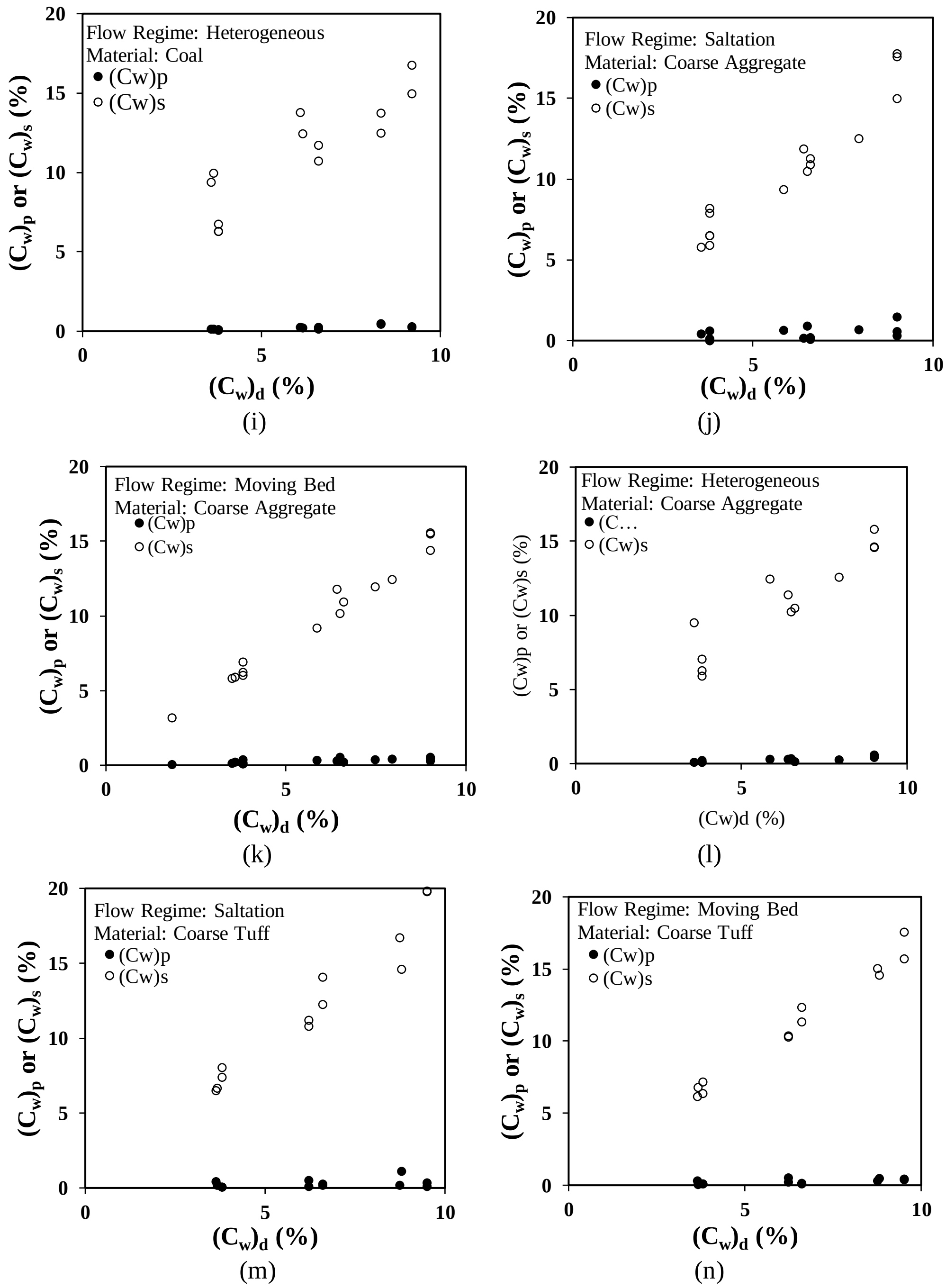
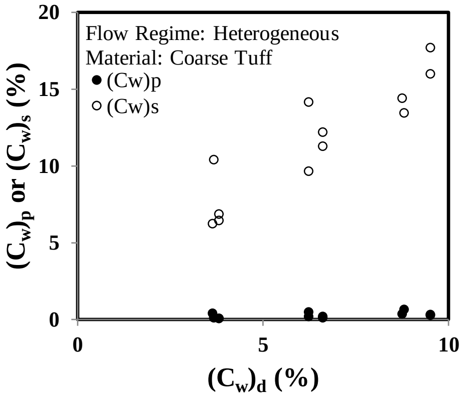
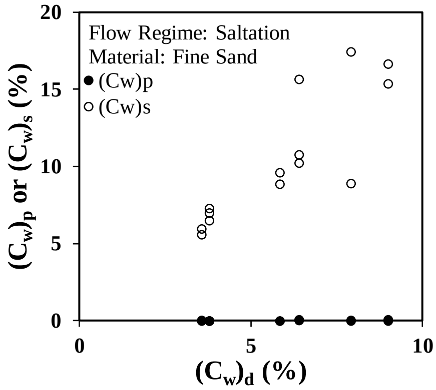


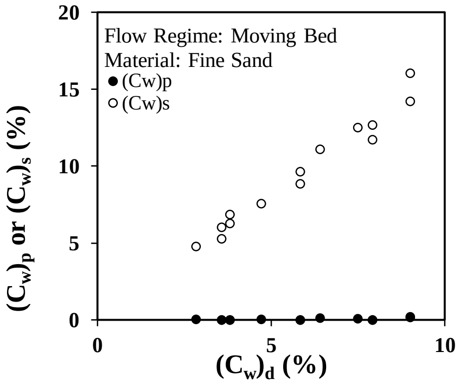
Figure 10. Variation of $(C_w)_p$ or $(C_w)_s$ with $(C_w)_d$ as a function of flow regime and material used (cont.)



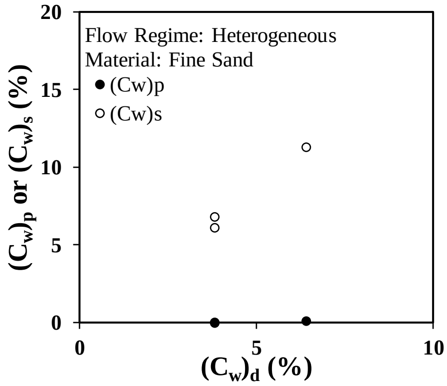
(o)



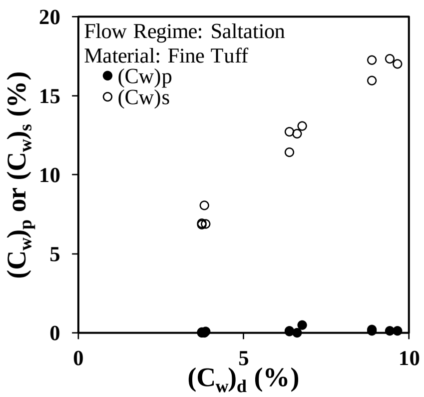
(p)



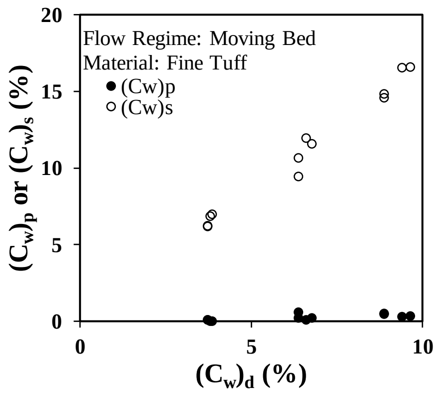
(q)



(r)



(s)



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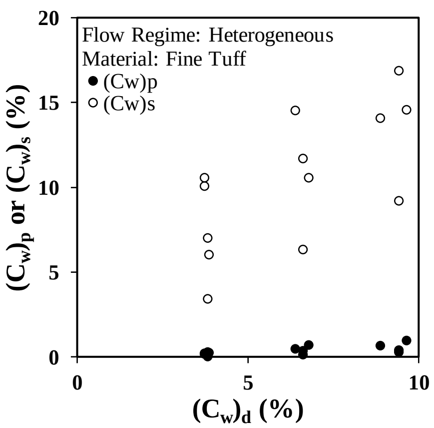

(u)

Figure 10. Variation of $(C_w)_p$ or $(C_w)_s$ with $(C_w)_d$ as a function of flow regime and material used

CONCLUSIONS

Apart from hydraulic conditions causing high friction losses in pipeline systems, the conveyance of solid particles through pipelines can also result in the undesirable abrasive action on pipes and the moving parts of centrifugal pumps. To mitigate this wear effect, one alternative solution is to use a water jet pump alongside a centrifugal pump in the pipeline system. The experimental study led to the following conclusions:

(1) Of all the water jet pumps tested and listed in Table 1, WJP 5.3 demonstrated the highest efficiency of η=0.329. This was achieved through an area ratio of driving nozzle to mixing chamber of A_n/A_{mc}=0.198, a non-dimensional driving nozzle location ratio of x/L_{sn}=0.84, a mixing chamber length to mixing chamber cross-section dimension of L_{mc}/D_{mc}=8.66, and a diffuser angle of θ_{ds}=3.53°.

(2) From the plot of pump efficiency η versus flow ratio M (Figure 9), it was concluded that for the water jet pump of WJP 5.3, the highest efficiency of η=0.329 was obtained at M=1.62.

(3) A Flow Division Unit was added to the test setup in order to reduce the number of solid particles passing through the centrifugal pump. Seven types of materials were used to create a slurry mixture with varying concentrations, and regardless of the type of solid material tested, the concentration of solid particles passing through the centrifugal pump did not exceed 10% of the initial concentration.

(4) It was observed that coarser solid particles move towards the outer branch of the flow division unit while fine particles tend to move towards the inner branch. This phenomenon was confirmed by comparing the measured data of coarse aggregate versus fine sand and coarse tuff versus fine tuff materials. In other words, fine particles are more effectively distributed between the two branches of the flow division unit than coarse particles.

(5) The slurry flow regime during operation also has an effect on the performance of the Flow Division Unit. The moving bed regime near the critical flow velocity was found to be more stable than the other flow regimes for all types of materials tested. A high scattering of concentration data was obtained from saltation and heterogeneous flow regimes, especially for low concentrations of materials introduced to the test loop.

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