Energy Saving During Pulp Screening Through Addition of A-PAM

by

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Abstract

Pulp screening is an important operation in the manufacture of pulp and paper industry. Through the pulp screening process, low quality pulp and other contaminants are removed to form high quality pulp stream. However, this process consumes a significant amount of electrical energy. Turbulent fluid exerts frictional drag on all solid bodies present in the flow. Drag can be reduced in various ways that will consequently diminish the pumping and pulp processing cost. The frictional drag of turbulent flow can be dramatically reduced by dissolving a minute amount of long-chained polymer in water. Unfortunately, the mechanism of Drag reduction by polymer additives with pulp is poorly understood.

In this work, the effect of polymer additives and surface contour modification on turbulent drag reduction in a pressure screen was studied with 0%, 1% and 2% pulp concentration. Drag reduction was measured for Northern Bleached Kraft Pulp in presence of APAM with a rotational speed of up to 1600rpm. Three different rotor power capacities were studied in presence of pulp, polymer additives and pulp with polymer additives for three different feed flow rates. Four different polymer concentrations were used during the experiment. 1% consistency pulp with 100 ppm polymer in EP rotor shows effective drag reduction of than 1% pulp consistency alone. At highest tip speed 15.43m/s drag reduction of EP rotor for 455 l/min flow rates of 1% consistency pulp with 100 ppm polymer is 38%±0.9%.

Additionally, a rotor having longitudinal ribs in the stream wise direction is studied. Literature shows that up to a 40% drag reduction [1] can occur by riblets along the stream wise direction in a turbulent flow regime with polymer additives. In this study, a ribs rotor having \( s^+ = 30 \), the spacing between two ribs is 2.3mm, height of the ribs is 1.15mm and thickness is 0.5mm was studied. Hydraulically smooth rotor takes less power than rib rotor for water and pulp solution.
Riblet geometry increases drag reduction at tip speed 10m/s to 90%±3.4% for 455l/min flow rate in presence of 100ppm A-PAM with 2% consistency pulp.
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Cp = Power coefficient
ρ = Density of fluid
$V_t$ = Rotor tip speed
μ = Dynamic viscosity of fluid
D = Diameter of rotor
$\tau_w$ = Shear stress of the wall
$\nu$ = Kinematic viscosity of the fluid
$u^*$ = Friction velocity
$\omega$ = Angular velocity
Re = Reynolds number
$P_n$ = Non-dimensional power number
List of Abbreviations

APAM = Anionic poly-acrylamide

PPM = Part per million

LDV = Laser doppler velocimeter

DR = Drag reduction

RMS = Route mean square
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Dedication

To my great parents
Chapter 1 Introduction

High-speed rotational flows are found in numerous industrial applications, for example oil refinery, sewage treatment plants, cement industry, food industry, paper industry etc. However, these flows often consume a great deal of energy. This accompanied with the sharp rising cost of fossil fuel and its limited availability has lead to the development of a keen interest in turbulent drag reduction methods. Pulp and paper industries use almost 30% of electrical energy produced in Canada [2, 3]. During papermaking, cellulose pulp suspensions are processed through a variety of different mechanical processes, many of which consume enormous amounts of electrical energy. Pulp screening is a technology which removes unwanted contaminates including unpulped pieces of wood (shives), bark, plastic, adhesives and other oversized particles. Another application of screening is fiber fractionation or separation of pulp by fiber length. The entire pulp screening processes ultimately requires a great amount of energy. When processed in the turbulent regime, energy required to transport and process suspension can be minimized. The whole process in papermaking is costly and takes high energy. Reducing power by a small fraction could lead to large financial saving.

Throughout the screening process, a low concentration pulp suspension flows between a stationary cylindrical screen plate and high-speed rotor. The pulp flows down between the screen plate and the rotor. The high quality pulp fibers preferentially pass through the screen plate and out through an accept port, while the remaining fibers and debris, continues down the feed side of the screen plate and out of a reject port. Industries used two types of screening processes: inflow and out flow screens. In outflow screening processes the accept passes radially through apertures outside the cylinder while the feed passes into the center of the cylinder. The inflow screen is opposite of outflow screen, where they accept passes through the apertures into the
cylinder and feed passes along the outside of the cylinder. Figure 1.1 shows a typical pressure screen.

A pressure screen consists of three main parts: screen basket, rotor and housing. Researchers have been trying to understand the hydrodynamics of the flow phenomena in and around the apertures in the cylinder. A pressure screen cylinder has apertures, which can be either
holes/slots of varying widths and diameter. It can also has smooth or contoured profile. Another application of screening is fiber fractionation which separates fibres by their geometry. For fiber fractionation typically the holed screens are used as they have wide open area compared to slotted screens. Holed screens are typically used for knot removal with aperture diameter range of 6 to 20 mm and for screening and fractionation with hole diameters of 0.8 to 3mm [4].

In the screening operation, the screen rotor plays a vital role. There are two types of rotors used in screening processes: solid core and foil rotors. The rotor creates a high tangential flow along the screen surface; it also generates large pressure difference across the screen plate [5].

The measured torque for a solid core or smooth rotor is a function of the rotational speed, the spacing and the fluid rheology. Any element in the rotor surface changes the torque, which depends on seven parameters: fluid density $\rho$, viscosity $\mu$, radius of inner cylinder, annular spacing, angular speed of rotor $\omega$, element height and the torque required to drive the rotor without element [6]. Foil rotors (EP) are similar in concept to the airfoils used on the wings of aircraft and allows the flow to pass over both the upper and lower surface of the foil.

Olson, Turcotte and Gooding [7] experimentally found that the nondimensional power coefficient for the screening rotor is independent of Reynolds number, with power coefficient defined as

$$C_p = \frac{\text{Power}}{\rho V_t^2 D^2}$$

(1.1)

Here, power is the power consumption of the rotor;

$\rho$ is the fluid density,

$V_t$ is the rotor tip speed,

$D$ is the diameter of the rotor.
Equation 1.1 shows that the power consumption of the rotor is proportional to the tip speed of the rotor cubed and a large reduction in power will be observed for the reduction of the rotor velocity. The performance of the screen depends on two functions of the rotor; firstly, the rotor provides high turbulence at the screen plate which helps to fluidize the pulp as well as provide high tangential velocity to the flow. Secondly, the foil on the rotor while passing along the feed side of the screen cylinder generates a negative pressure pulse, which black flush, the apertures and prevents the screen from plugging up. Two types of rotors are widely used in the screening processes; solid core and foil rotors. For low consistency and fine screening paper mills prefer foil rotors which are similar to the airfoils used on the wings of aircraft and allow the flow to circulate around the foil. Foil rotors are more effective as they offer greater control over the shape of the pressure pulses generated by the rotor. In this thesis, a foil rotor is used.

It is well known that a turbulent flow exerts frictional drag on all solid bodies present in the flow. The fact that the drag can be reduced has been the attention of several studies over the last several decades. Drag reduction can be achieved in many ways, for instance by dissolving polymers or other additives into the fluid or by modifying the surface structure on the solid boundaries in the flow. One of the most successful methods of drag reduction is achieved through the addition of small amount of high molecular weight polymers to the flow. In fact, very small quantities of this polymer can introduce profound effects on drag reduction. While some of the details of the mechanisms responsible for polymer drag reduction are still poorly understood, it is generally agreed that long chain flexible polymers act by absorbing and redistribution turbulent kinetic energy in the buffer layer. Drag reduction polymers are used in a number of different industries to reduce the cost of energy, e.g. oil refinery industry, marine
vehicle and pipe line flow. However, this technology has yet to implement in the paper making industry.

Additional reduction in turbulent drag can be achieved through the use of surface, i.e., stream wise grooves placed along surfaces, which restrict the turbulence intensity in the span wise direction. The flow over a surface with tiny ribs (riblets) aligned in the stream wise direction has been shown experimentally to reduce turbulent drag in a number of different flow fields. Such riblets may be triangular, rectangular or blade shaped and may further modified by varying their angles and configurations. Like polymer drag reduction, this technology is not currently implemented in paper making processes.

The main objective of this thesis is to investigate the effect of polymer additives and surface contour modification on turbulent drag reduction in a high-speed rotational flow with applications to the pressure screening process in papermaking. A laboratory modified multi rotor pressure screen having 8-inch diameter cylinder (MR 8) is used to measure the power required to drive the rotor at high speed (200-1600 rpm). A serie of five experimental studies were conducted to investigate the effect of polymer on pulp in pressure screening. Experiments were performed at Reynolds numbers in the range of 1.1 X 10^4 to 14 X10^4. Three different rotors were considered: a rotor with a plane surface, one with small riblets aligned in the flow direction and an industrial EP rotor. Anionic hydrolyzed polyacrylamid (APAM) is used as the polymer phase with different consistency of pulp (0%, 0.1%, 2%) during the experiments.

A review of the literature regarding to this study is presented in chapter 2, followed by a detailed objective of this thesis. Experimental equipment and procedure used throughout the research is
described in Chapter 3. Data analysis is represented in Chapter 4 and an overall summery of the thesis is given in Chapter 5.
Chapter 2 Literature Review

2.1 Drag Reduction

A flowing fluid exerts frictional drag on all solid bodies present in the flow. As a result, the drag reduction has been the attention of several studies over the last several decades. The study of drag reduction dates back to the 1930s. Before the 1960s, the main focus of drag reduction research was aimed at methods for decreasing the surface roughness of the solid body. In recent years, the drag reduction studies have been focused on the flow over a surface where tiny ribs (riblets) aligned in the stream wise direction are symmetrically attached. These studies had been motivated largely by their occurrence in nature, e.g. consider the micro surface structure of the sharkskin. In this chapter, a review of drag reduction by polymer additives will be given, which will cover the mechanism of drag reduction by polymer additives and experimental studies. After that a review of drag reduction by riblets will be given, which includes the mechanism of drag reduction by riblet geometry and experimental studies. After that, a review of drag reduction by polymer and riblets will be described followed by pulp additives.

2.2 Drag Reduction by Polymer Additives

2.2.1 Background

There is an abundance of literature showing that drag reduction can be obtained in many ways. These include dissolving polymers or fibrous additives into the fluid or by modifying the surface structure on the solid boundaries in the flow. The most significant drag reduction can be obtained through the addition of high molecular weight polymer in the fluid [8, 9]. Researchers have found that high level of drag reduction was obtained even at very low polymer concentration for very high molecular weight additives such as polyethylene oxides, polyacrylamid,
carboxymethycellulose and guar gum [10]. Pulp additives have similar effect on drag reduction of turbulent flow. Daily and Tsuchiya(1959), Bobkowicz and Gouvin (1965), Kerekes and Douglas(1972) obtained data for drag reducing characteristic of nylon fiber. Hoyt (1972) obtained data for glass and acrylic fiber, asbestos fiber, rayon fiber; Mason(1950), Daily and Bugliarello (1961), Mih and Parker(1967) obtained data for the drag reducing phenomena of suspension wood pulp fiber. Raiden. I, Zakin .J.L, Patterson (1975) examined that non fibrous particles of many shapes, such as, spherical, needle shape, platelet do not exhibit drag reducing phenomena at a high flow rate. However, they obtained a tremendous amount of drag reduction phenomena with natural and synthetic fiber.

On the other hand, asbestos reduces drag considerably compared to other microfibers such as ethylene glycol and glass microfiber [11]. Synergism in drag reduction by the polymer-polymer and polymer fiber mixture has been studied in a re-circulatory turbulent flow of water to study the shear stability. One of the most important limitations of using polymer for drag reduction is degradation. During drag reduction experiments with polymer severe shear forces are produced by the centrifugal pump which causes degradation of the polymer. This degradation has an effect on the drag reduction characteristics of polymer. Experimental study showed that Methofas is a highly shear resistance polymer than other cellulose derivatives [12]. Reddy et al (1985) observed that drag reduction by the polymer-polymer mixture depends on its composition, flow rate and polymer spices in the mixture.
The friction factor ($f$) relation for a given polymer solution in a pipe flow can be described by two parameters, (1) the onset of drag reduction and (2) Prandtl karman slope increment. Figure 2.1 shows polymer induced drag reduction phenomena inside of a pipe. Drag reduction of a pipe flow by polymeric solution is bounded between two universal asymptotes: (1) Prandtl–karman law asymptote (Newtonian turbulent flow) and (2) maximum drag reduction asymptote or Virk asymptote. In between these two asymptotes there is a zone called the polymeric zone. If the friction drag for pipe flow is plotted on the Prandtl–Karman co-ordinates, for high flow rate the onset of drag reduction starts to occur and depart from the Prandtl-Karman law, this is called
Prandtl-Karman slope increment, which merges with the maximum drag reduction asymptote [9]. It is noticeable that after the onset of drag reduction, for a given Reynolds number, drag reduction increases with polymer concentration and merges with the MDR asymptote. Similarly, for a given polymeric concentration, with increasing Re number, drag reduction initially increases and submerges the MDR. Moreover, the two slope increment points for constant Re and fixed concentration of polymer are not same [13, 14].

Drag reduction by polymer solution with addition of fibres was done by Sharma et al to study the synergies that were first represented by Lee et al (1974). Sharma et al [12] studied the drag reduction phenomena by centerline injection of long hair like fibers in the axis of a pipe flowing with a homogeneous solution of hydroxypropylmethyl cellulose (commercially known as Methofas). Asbestos fiber suspension having a concentration of 300 parts per million by weight was injected at the centerline of the pipe carrying 250-2000 ppm (weight) homogeneous solution of hydroxypropylmethyl cellulose. Sharma found that in absences of fiber in any polymer solution the friction reduction for any concentration occurs when the threshold value of the Reynolds number is exceeded. This threshold Reynolds number was observed to decrease with the increase of polymer concentration. Pipe friction factor also increased with the increasing polymer concentration. Reynolds number based on water viscosity obtained best drag reduction for Methofas solution of 250 ppm. It has been found that drag reduction can be obtained even at a low Reynolds number (main flow) by injecting a small amount of long hair like fiber into the axis of the pipe. With 30 ppm concentration of fiber, drag reduction by fiber alone is 24% and polymer plus fiber is 31%. On the contrary, for 120 ppm concentration of fiber and polymer plus fiber the drag reduction is found 45% and 50% respectively.
It is anticipated that there is a critical polymer concentration where the drag reduction is maximum. Maximum drag reduction is considered as a function of polymer concentration and for disk flow field that is fairly broad. In spite of polymer DR increases with polymer concentration, % drag reduction efficiency is more or less independent of concentration for a broad range of polymer concentration [15].

Rotational flow between concentric cylinders was studied in presence of polymer additives to understand the DR effect of polymer. In disk geometry, the percentage of DR reduces by the increases of Reynolds number. Polymer additives will lose their efficiency as a drag reducer if they undergo mechanical degradation at high shear rates (corresponding to high Re number). It has been hypothesized that the network structure of polymer becomes weak when they enter high shear rates at higher Reynolds number [16, 17].

![Figure 2.2 Reynolds number vs drag reduction in a disk geometry [16]](image)


## 2.2.2 Studies on The Mechanism of Polymer Drag Reduction

Many researchers have performed different experiments for both practical and fundamental purposes in an effort to determine how the polymer phase reduces drag in a solution. Different research groups appear to have come to somewhat different conclusions. Most studies tried to explain the onset of drag reduction with either viscous effects or elastic effects. However, these are two classes of explanations and the researchers with viscous theory tend to disagree with researchers supporting the elastic theory and vice versa. There are also some recent studies indicating that the theories may not be as fundamentally different as they appear, since the elastic effect could be interpreted as a viscous effect [13].

The basic theories are based on the effects of two underlying mechanisms relating to polymer stretching on the flow. The first theory is focused on viscous effect (Lumley 1969, L’vov et al.2004, Ryskin 1987) and the second one on elastic effects (Joseph 1990, Tabor & de Gennes 1986) [13]. The viscous effect of elongational viscosity is due to the stretching of polymers in a turbulent flow, which increase the effective viscosity. The drag reduction occurs in polymer solution because of dynamic interactions between polymer and turbulence. Two results have been found, in the first case, no significant difference in the skin friction has seen or other flow character compared with Newtonian fluids for laminar pipe flow. In the second case, drag reduction first observed depends on the number of monomers in the macromolecule when the diameter and Reynolds number are fixed [18]. It is predicted that for a wall bounded turbulent shear flow polymers are stretched just outside the viscous sublayer - buffer layer. It is assumed that the strain rate and vorticity fields associated with the buffer layer influence full extension of the polymer, which increases the corresponding elongation viscosity.
There is evidence to believe that polymer drag reduction depends on time criterion. The time criterion is a criterion for drag reduction to occur, i.e. it is a way to predict the onset of drag reduction. The criterion being that the polymer relaxation time has to be longer than a characteristic turbulent length scale near the wall. The criterion has some support, but is somewhat limited since according to it there is no dependence on polymer concentration [13],[19].

It has been predicted that the large increase in the effective viscosity will suppress turbulent fluctuation just outside the viscous sublayer, which increases the buffer layer thickness and reduces the wall friction. L’Vov et al [20] proposed that a space dependent effective viscosity is the result of polymer stretching, a phenomenon which was shown to grow linearly from the wall. The drag reduction of polymer is therefore the result of the suppression of the Reynolds stress in the elastic sublayer. An expression has been derived for the mean stream wise velocity profile, which agrees well with the ultimate profile given by Virk.

Virk [9] showed in his experiment that in a particular species- solvent pair the onset of wall shear stress is independent of the pipe diameter, polymer concentration and solvent viscosity but changed inversely with the two to three power of polymer radius of gyration or the molecular weight. Based on the law of the wall co-ordinates there are two zones, from the outward of the wall, the viscous sublayer and the Newtonian plug. Virk described in his work that in between these two zones there is another zone, which he called elastic sublayer. He observed that elastic sublayer is a zone occurring in the solution because of the stimulation of polymer molecules by the turbulent shear flow. With increasing drag reduction, this sublayer tends to increase and when the maximum drag reduction occurred, the elastic sublayer spread throughout the entire cross section.
The elastic theory postulates that the increase in effective viscosity is small and insignificant and the elastic energy stored by the partially stretched polymers is an important variable for drag reduction. The elastic theory explains that the drag reduction occurs when the cumulative elastic energy stored by the partially stretched polymers become equivalent to the kinetic energy in the buffer layer. In order to obtain drag reduction, the relaxation time of the polymer should be long enough to transport the elastic energy from the near wall region to the buffer or log layer. The elastic energy obtained near the wall is otherwise released there and an equilibrium state exists in terms of energy change, resulting in no drag change.

A summary of current understanding of the physical mechanisms of polymer drag reduction is that after adding a certain amount of polymer into a turbulent boundary layer, the effective viscosity increases due to the stretching of the polymer molecules in the inertial sublayer.

### 2.2.3 Experimental Study of Polymer

Ptasinski et al [21] has done LDV (Laser droplet velocimetry) experiments for a fully developed turbulent pipe flow with polymer solution of partially hydrolyzed polyacrylamid and water. Around 60-70% drag reduction was found for three different concentrations of polymer solution. They observed the effect of polymer concentration on turbulence intensity, mean velocity and total shear stress. They also noticed that there is an increase of the slope of the logarithmic profile and in terms of mean velocity profile the thickening of buffer layer occurred. The drag reduction measurement was in terms of fanning friction factor, which is a function of wall shear stress and is the reason that viscosity does not have a constant value for non-Newtonian fluid such as a shear thinning polymer solution.
Fanning friction factor,

\[ f = \frac{\tau_w}{\frac{1}{2} \rho U^2} \]  

(2.1)

Where,

- \( U \) = mean velocity of the fluid in the pipe
- \( \rho \) = density of the fluid
- \( \tau_w \) = wall shear stress

They also found that for lower polymer concentrations the peak of the root mean square of the axial velocity fluctuation is increased, whereas for highest concentration the height of the peak merges with the value found for water. However, they observed that Reynolds stress strongly decreased with high concentration of polymer but remained non zero. Since the axial velocity fluctuations increased, but the Reynolds stress decreased, which implies that the radial fluctuations were decreased.

Liberatore et al [22] studied the relationship of turbulent drag reduction and molecular weight distribution for aqueous polyacrylamid (PAM) solution of concentration 200, 500 and 1000 ppm. The experiment was done by a circulation flow in a rectangular channel, which has a flat wall and a wavy wall. The shear induced structure formation of the solution is determined by rheological and rheo-optical measurements over a range of shear rates. They showed that molecular aggregation could be an important factor to understand drag reduction. Their results showed that drag reduction does not always correlate with loss in molecular weight. In contrast, in previous studies it had been shown that there is correlation between the molecular weight and the amount of drag reduction. In high shear rates polymers tend to degrade and the drag reduction is reduced. Liberatore et al showed that the reduced DR could occur even when the polymers are intact. They therefore speculated that the reduced drag reduction is probably due to
aggregates breaking up and that drag reduction cannot be understood. They found 58% drag reduction for 1000ppm and viscosity measurements were carried out to monitor the degradation of polymer solution.

Ptasinski et al [23] had done direct numerical simulation for channel flow, their polymer model was solved continuously with the flow equation i.e, by the deformation of polymer in the flow which in carriage the flow structure by introducing polymer stress in the flow. Their simulation result was close to the maximum drag reduction of Virk (1975) asymptote. The velocity fluctuation in the span wise and wall normal direction decreased continuously as a function of drag reduction. However, the root mean square of the stream wise fluctuation increased in the beginning and after the maximum drag reduction it started decreasing. They compared their result with the experimental result of Ptasinski (2001) and found significant effect on drag reduction. The Reynolds shear stress decreased and to compensate the polymer stress increased. For the simulation close to maximum drag reduction, the polymer stress contribution was 40%-50% of the total stress. When there are no polymers in the flow, the total stress would be the sum of the viscous stress and Reynolds shear stress.

Gillissen et al [24] used direct numerical simulation to study the drag reduction phenomena of rigid polymer in a channel flow, however it should be noted that the interaction between fiber was neglected. They also compared their result with previous data of Na- polyacrylate by Sasaki(1991) and partially hydrolyzed polyacrylamid by Virk (1975, 1977). Their simulation verified three physical observations:

First of all their Direct Numerical simulation described in a good way the velocity profiles by empirical parameterization proposed by Virk (1975)[9]; secondly, the drag reduction efficiency,
which is dependent on elastic layer and independent of the frictional Reynolds number and finally it noted that the drag reduction efficiency increases linearly with polymer mass concentration.

Researchers have done drag reduction studies of turbulent flows by using polymers in pipe flow and channel flow. Warholic (1999)[25] has done wide range of experiment to investigate the effect of the concentration of polymer, mixing process and Reynolds number on turbulent drag reduction by using polymer in a fully developed channel flow. The solution was made by injecting Percol 727, which is a co-polymer of Polyacrylamide, and sodium acrylamide with a commercial mixing device in deionizer water. When maximum drag reduction occur Reynolds stress was observed to be zero for the whole cross section of the channel. 10-69% of drag reduction was found by varying the concentration inside the channel [25].

### 2.2.4 Drag Reduction at Higher Reynolds Number

The majority of laboratory tests studying the effect of polymers on DR have been done on moderate Re number [22]. High Re has been addressed by the HIPLATE experiment completed recently by Ceccio [13] at high Re number, at speed up to 19.9 m/s using a range of polymer types and concentration. For 19.9 m/s speed almost 70% of drag reduction was found. Increasing molecular weight and increasing flux of polymer results increase Drag reduction. Furthermore, drag reduction for high molecular weight is higher at high speed. After the MDR the continued processes of mixing lead to a steady decrease of DR. The point of the development of DR region varied with free stream speed, whereas decrease of DR is much less speed dependent. This study also shows that higher molecular weight polymer appeared to undergo degradation, which limited their drag reduction effectiveness [22] [26].
2.3 Drag reduction by Riblets

2.3.1 Background

Among the various viscous drag reduction techniques, laminar flow control, slot injection, polymers; researchers have been examining surface modification with riblets with particular interest. The investigation of passive drag reduction devices, turbulent boundary layer flows over small longitudinally grooves, known as ‘Riblet’, was initiated by Walsh and his co-workers [27-29]. It is well known that turbulent skin friction can be reduced by implementing small flow aligned riblets (Different laboratory has done many experiments: Walsh & Weinsteint 1979; Walsh 1980,1982, 1983;Walsh and Lindemann 1984; Bechert, Bruse and huge 1997, 2000 ;Choi 1987; Choi, Gadd, Pearcey 1989; Bechert & Bertenwerfer 1989; Luchini, Manzo, Pozzi 1991,1992; Hall, Joseph 2000; Liu, Christodoulou, Riccius 1990; Wang, Lan, and Chen 2000). Different research laboratory has done independent measurements on channel flows with various shapes of riblets such as rectangular, triangular, semi circular etc. Drag reduction of the order of 10% as compared to a smooth surface has been found using a surface with riblets by using baby oil [30].

It has been found that in order to obtain turbulent drag reduction with riblets the physical dimension of the riblets cannot be too large. Researchers described the mechanism of drag reduction by riblets using two parameters, $s^+$ and $h^+$ which are two nondimensional numbers
\[ s^+ = \frac{s u^*}{u} \]  

(2.2)

Where,

\( s^+ \) = nondimensional spacing,

\( u^* \) = friction velocity,

\( s \) = spacing between two ribs

\( u \) = kinematic viscosity of fluid

\[ h^+ = \frac{h u^*}{v} \]  

(2.3)

Where,

\( h^+ \) = nondimensional height,

\( u^* \) = friction velocity,

\( h \) = height of the rib

\( v \) = kinematic viscosity of fluid

Different kinds of riblet geometries are possible, for example, V-groove [27], rectangular riblets, and triangular riblets [31][28, 30]. Walsh and his co-workers found that a triangular riblet having a height to spacing ratio of one, provided optimum drag reduction performance [27]. Furthermore, they found that when \( \frac{h}{s} \approx 1 \) exhibited -

(i) For non-dimensional riblet spacing \( s^+ < 25 \), riblet reduced drag and a maximum drag reduction of 10% occurred at \( s^+ = 15 \) [28].

(ii) For non-dimensional riblet spacing \( s^+ > 25 \), riblet enhanced drag, by as much as 30% when \( s^+ \approx 50 \).
When, $h^+ \leq 15$, the drag data for symmetric v-groove riblets scaled well with $s^+$ independent of $h^+$. They concluded that the burst frequency for riblets is approximately the same as that for a flat plate but the turbulence intensity is reduced. From various experiments they found that the lateral spacing $s^+$ of riblets exhibiting the highest drag reduction happened at $S^+ \approx 15 - 17$. Drag reduction can be seen up to $s^+ = 30$ [28],[32] after this limit drag starts to increase. Internal flows of air and water inside a riblet-lined pipe [1, 33-35] show the same behavior as the external flows over a riblet surface [36].

Walsh et al [28] examined the riblets manufacturing techniques for aircraft application. They tried to investigate whether net drag measurements of the riblets surface enhanced by combining the riblets with another drag reduction method by Large eddy breakup devices. This time the experiments were run at higher Re numbers and free stream velocity was 45 m/s. They concluded that the riblet drag reduction is essentially additive that obtained with a large eddy-breakup device. Other than machined surfaces, they used vinyl riblets that would provide greater dimensional and surface quality as well as being more practical. Their experimental data suggest that lightweight vinyl riblets with adhesive backing have the same drag reduction performance comparable to the machined aluminum model. They compared the aluminum riblets data with vinyl riblets, which were made out of a thin vinyl sheet for different rib geometry. The vinyl model was designed to have the same physical dimension as the aluminum model, but the manufacturing process produced vinyl riblets having the same spacing but a smaller height than the aluminum model. The aluminum model produced 7 percent reduction in skin friction whereas the vinyl riblets produced 5 percent drag reduction. When the $s^+$ was reduced to below 10 the model which had smaller dimensions acted like a flat plate. The maximum drag reduction for all models occurred for $s^+ = 15$, whereas the value of $h^+$ varied due to the variation of the physical
height. Another model was designed with a very small dimension to reduce the physical size of the riblets and to determine a drag reduction at high velocity. Modification of small physical size of v-groove geometry result in blunt or non-uniform riblets, which does not produce any additional drag reduction.

Researchers have done different drag reduction experiments by varying the $s^+$ and $h^+$ to determine the optimal value of this two parameter on drag reduction. The optimum value of this two parameters lies in low-of-the-wall. Von Kerman in 1936 gave the idea of the-law-of-the-wall which is applicable for the parts of the flow which are close to the wall ($<20\%$ of the height of the flow).

The ‘law-of-the-wall’ is

$$u^+ = \frac{1}{k} \ln y^+ + C^+ \quad \text{with} \quad y^+ = \frac{y u^*}{\nu}; \quad u^* = \sqrt{\tau_0 / \rho}; \quad u^+ = \frac{u}{u^*}$$

(2.4)

Where,

- $\nu$ is the Kinematic viscosity
- $u^+$ is the dimensionless velocity
- $u^*$ is the friction velocity
- $k$ is the kerman constant
- $U$ is the fluid velocity parallel to wall
- $y^+$ is the nondimensional $y$
- $\tau_o$ is the wall shear stress
- $\rho$ is the density
- $c^+$ is constant
The turbulent boundary layer has three segments, a viscous sublayer with $y^+ \leq 5$; the buffer layer with $5 < y^+ < 20$ and logarithmic layer with $y^+ > 20$. In each layer the velocity profile is different.

$u^+ = f(y^+)$, i.e. $u^+$ is a function of $y^+$ only.

This comes from a reasoning based on that when turbulent flows over a solid surface there will be a thin region near the wall, where the velocity gradient is large. In this boundary layer it is reasoned that the width of the pipe is more or less insignificant. So very close to the wall, in the inner layer the viscosity is important.

Very close to the wall $u^+ = y^+$; (Viscous sublayer) as the distance from the wall is increased the importance of viscosity is decreased. In order for $\partial U/\partial y$ to become independent of the viscosity for very large $y^+$ the analysis gives that $u^+ \sim lny^+$[37].

Liu (1990)[33] measured values of friction factor for ribbed pipes and pipes lined with smooth film. During the experiment $s^+$ was varied, to determine optimal value of $s^+$. Drag reduction was found when $s^+ = 3$ up to $s^+ = 23$, further increase of $s^+$ at larger speeds decreased drag reduction. Maximum drag reduction 5-7% occurred when $s^+ \approx 11 \sim 13$ [35].

A simple method was predicted by Baran, Quqdrio(1993) [38] for the drag reduction performances of a given ribletted surface, on the basis of the phenomenological and theoretical analyses of the riblets flow interaction. This method used the experimental information provided by direct friction force measurements of Walsh and Lindemann (1984) [28]. The drag prediction
method reproduced the data for various ribletted surfaces, which was compared with the well documented experimental data of different laboratories and the finding looked similar.

When a flow is passed over riblet surface the thickness of the viscous sublayer, the region of buffer layer is greater than that for the smooth surface, which implies that riblets plate posses drag reduction property. Laser Doppler velocimeter (LDV) and hydrogen bubble flow visualization techniques were used for measuring the characteristics of turbulent boundary layer flow over the ribs surface [39]. Maximum value of turbulent intensity was increased by 6.7%.

Recently some experimental research has been done with 3dimensional riblets such as shark skin, sailfish skin etc. To deduce the possible boundary layer control mechanisms like fast-swimming sharks have. Lang et al [40] completed experimental work using a water tunnel facility to investigate the flow field over and within a bristled shark skin model submerged within a boundary layer. The shark skin model was designed based as scale length ~170 µm, scale width ~140 µm, rib spacing ~42 µm and rib height ~8 µm. From their experiments, it is postulated that the unique microgeometry of bristled shark skin can decrease overall drag. In comparison with 2D riblets by Bechert and Bruse(2000)the behavior of 3D riblets is actually 1.7% inferior. For short 3D riblets the optimum drag reduction occurs at a lower rib height than for long 2D riblets.

Samni et al [41]numerically investigated the optimum size of the riblet by studying five different cases with different spacing, within which drag reduction and drag increase were expect to occur. Thin rectangular riblets were distributed uniformly along one of the channel wall. Direct numerical simulations of fully developed turbulent flow over the riblet were carried out. They seted the riblets thickness/spacing ratio to 0.02 and height/spacing ratio was fixed at 0.5. The
maximum drag reduction was obtained at about 11% when the spacing was 18 viscous units. They also noticed the drag reduction increased when the spacing is larger than 40 wall units. Their spacing range showed excellent comparison with the experimental data of Kim et al [42] in both reduction and increase of drag. Although, many experiments have been done on pipe flow or plate flow (tank) only a few experiments have been done on rotary devices with riblets. Hall et al [43] tested water in a rotating cylinder drag balance device to estimate the drag reduction by surface like riblets. The apparatus was designed with two concentric cylinders; the outer cylinder rotates to drive fluid in the gap resulting in a shear stress on the inner cylinder surface, which was measured as the torque applied to the inner cylinder by the fluid. 114µm saw tooth riblets were molded onto a PVC adhesive film which could be easily placed and removed from the cylinder surfaces within the gap. The instrumentation was done by the calibration of laminar flow and the result was compared with turbulent flow result of G.I Taylor (1936). The experiment was run with an 80 wt% glycerin in water solution and thermocouples were placed in each cylinder to measure the temperature of the inside of the outer cylinder and outside of the inner cylinder. Four different sets of cylinders with varying gap size were used during the experiment. Triangular cross section riblets known as sawtooth or V-groove riblets were used in three ways, (1)riblets in inner cylinder and plane sheet in outer cylinder, (2)both cylinders with riblets, (3)ribs in outer cylinder and plane PVC in inner cylinder. The maximum amount of drag reduction of approximately 5% was gained in the range of $10 < S^+ < 15$ when riblets were in inner cylinder. However, for the riblets in the both cylinder, it appears that outer cylinder riblets influence the inner cylinder stress measurements. Maximum DR increased to 6-8% in the range of $8 < S^+ < 12$. 
2.3.2 Mechanism of Riblet Drag Reduction

The mechanism of drag reduction by riblet is not yet fully understood. Although there is evidence that riblets influenced burst frequency, researchers have made conflicting observation as: (1) burst frequency increased by riblets Hooshmand et al [44, 45], (2) unchanged by Walsh, Bacher & Smith [27, 44, 46] (3) reduced by Gallagher & Thomas, Savill [44, 47, 48]. Karmer (1939) gave the first hypothesis on drag reduction mechanism. He concluded that the riblet surface redistributes the shear stress, with a high concentration at the protruding parts of the surface [31]. Bacher & Smith considered the interaction of the counter-rotating longitudinal vortices with the small eddies created by them near the peaks of riblets, arguing that the secondary vortices would act to weaken the longitudinal vortices as well as to retain the low-speed fluid within the grooves. Choi (1984) discussed the mechanism in terms of the increase of span wise effective viscosity and the thickening of the viscous sublayer, which is analogous to the case of drag-reducing polymers [44].

To give a more satisfactory explanation of how these riblets reduce drag, Bechert et al [49] gave an explanation of the drag reduction effect by considering the mean flow of the viscous sublayer where the riblet surface is immersed. Bechert (1989) theoretically investigated the viscous sublayer of turbulent boundary layer on a surface having longitudinal riblets. They calculated the velocity distribution on different surface configurations by using conformal mapping. The geometry of riblets they investigated were riblets with sawtooth profiles, as is Walsh (1980, 1982 & 1984); riblets with trapezoidal grooves; two dimensional blade shape riblets, scalloped riblets, rounded ridges and convex riblets as is[27, 28]. They tried to locate the origin of the velocity profile that lies below the tip of the ribs and above the bottom of the valley between the ribs. The
distance from the ribs tip and the origin of the average velocity profile is known as ‘protrusion height’ as it determines how far the riblets will be extended into the boundary layer. For this they took saw tooth riblets where the riblet height and spacing is equal, $s^+$ was 15 wall units. From their calculation they found that the protrusion height for the riblet configuration is $h_p = 0.18s$ or $h_p = 2.7$. This meant that the rib tips produce 2.7 wall units above the origin of the velocity profile. From the definition of viscous sublayer theory the value of $y^+ = 5$ or $y^+ = 3$ for linear sublayer, that indicates riblets are imbedded in the viscous sublayer [49].

Bechert et al (1997) [31] made an attempt to improve the skin friction reduction from their previous drag reduction data, which was about 5%. In their experiments a surface with longitudinal ribs and additional slits were studied with lateral rib spacing of between about 2 and 10mm. Experiments were carried out for a surface with longitudinal blade ribs and with slits, during the experiments both the slit width and groove depth had varied separately and continuously. With closed slit and optimal groove depth an 8.7% skin friction reduction had found out. The experiment concluded that the slits in the surface has no contribution to the drag reduction. Their experimental results also supported the theoretical model proposed by Luchini(1992) [50, 51] and also gave a corelation between theory and experiments. The theory is based on the hypothesis that riblets hamper the fluctuating cross flow component near the wall, which reduce the momentum and reduced wall shear stress. Shear stress measurements were carried out with triangular and semicircular grooves.
Bechert et al claimed that their explanation and experiment also matches with Luchini et al [50]. They bring the matter to a conclusion that drag reduction is induced by the hampering of the fluctuating cross-flow component $w'$ is because of the longitudinal ribs, which rectifies the turbulent flow in mean flow direction [49] [31]. Figure 2.3 shows the location of longitudinal flow in rib geometry. If the cross-flow fluctuation $w'$ close to the surface is reduced then the turbulent momentum transfer close to the surface will also be reduced, consequently, the shear stress will be decreased.

Drag reduction of riblet surfaces are dependent on the spacing and height of the riblets in law-of-the-wall variables despite the consequence of free stream Reynolds number [28]. An explanation behind this is that close to the wall the typical mean diameter of stream wise vortices is about $d^* = 30$ expressed in wall units [42]. In the case of drag reduction $0 < s^* < 30$, the longitudinal vorticies are larger in diameter $d^*$ than riblet spacing $s^*$. Due to the fact, most stream wise vortices stay above the riblets and vortices touch only the rib tips of the riblets in

![Figure 2.3 Viscous longitudinal flow on a ribbed surface [31]](image-url)
contrast to the smooth wall where the friction surface is greater. In case of drag increase $s^+ > 30$, longitudinal vortices are smaller in diameter $d^+$ than the riblet spacing $s^+$. As a result most streamwise vortices settle inside the riblet valley. These vortices interact actively with the increased wetted surface and consequently the skin friction increases [52, 53].

2.4 Polymer and Riblet Studies

Choi et al (1989) [54] experimentally measured the effect of U-groove riblets, polymer coating and the combination of two in a towing tank for drag reduction. Their results showed that the combination of riblet and polymer improved the drag reduction. Maximum drag reduction was gained 3.5% for nondimensional $S^+ = 8$, for combination of riblet and polymer. When polymer was sprayed over plane surface the drag reduction was 3.1%, certainly greater than DR 2.5% of riblet surface alone. Synergistic effect of DR occurred for large $s^+$ [55, 56]. Rohr et al performed two kinds of tests; on with a flat plate another with pipe flow. Free stream velocity and Reynolds number data indicated almost 8.1% drag reduction with riblets in a plate, whereas, with riblets in pipe friction reduction is three times than plate data. However, when polymer solution (polyacrylamide slurry) is combined with riblets in pipe flow; the total drag reduction is approximately equal to the sum of the drag reduction of two techniques used separately [55]. Koury et al determined drag reduction by riblet pipe is 1.6 times higher than smooth pipes when using 3wppm polyethyleneoxide polymer. They noticed that with increasing polymer concentration drag reduction by riblets decreases to 0.8 for smooth pipe of 10wppm polymer. For their experiment, they used V-grooves riblets with Reynolds number of 300-15000. It is postulated this is because riblets delay the polymer degradation caused by high shear stresses to a high Reynolds number [36].
Anderson et al [1] found 0-40% drag reduction with 100wppm guar-gum in a pipe lined with 0.15mm V groove riblets. Non dimensional riblets heights were $4 < h^+ < 90$. They determined that for solvent flow riblet pipe exhibited maximum 8% drag reduction at $h^+ \approx 15$, where the range was $4 < h^+ < 22$. They also observed that drag increased for $h^+ > 22$ and maximum 40% drag increased at $h^+ \approx 90$. For solvent, the behavior or drag reduction of the rib pipe relative to smooth pipe is same, which means riblets perform better with polymer.

### 2.5 Pulp Additives

Pulp fibres are individual wood cells, typically 0.5-4mm long and 20-40 microns in length. The large L/D ratio of fiber is the main reason of forming flocs in fiber suspension, which are typically a few millimeter long and once they generate, it is difficult to pull them apart. Researchers have discovered that drag reduction could be obtained when this aspect ratio (L/D) is about 30. Fluid like motion of pulp suspension has a great impact in the processing of paper making in pulp and paper industry. In the paper industry pulp suspension can be created with varying concentration of fiber, which can be expressed in terms of volumetric concentration, $C_v$, or a mass concentration, $C_m$(consistency), of fiber in water.

Fibre suspensions create coherent networks (inter fiber networks) which possess measurable strength. To move a pulp suspension a sufficient external force must be applied to overcome this network force. The fluidlike motion can be maintained by overcoming the suspension yield stress in a process called ‘fluidization’. To overcome the yield stress of fiber suspension this fluidize pulp suspension requires enough power.
In a pipe flow, as the velocity of the pulp suspension increases, the flow will pass through three flow regime due to the effect of yield stress, which are: Plug flow, mixed flow and turbulent flow. In the plug flow regime the pulp suspension act as a solid body and as the flow rate increases the pulp will try to move away from the wall and create a water annulus in between the plug and the flow. If the velocity of the flow is further increased, the pulp near the wall starts to fluidize which is called the mixed flow regime. The annulus near the wall now becomes the mixture of pulp and water. When at a very high velocity the yield stress in the pulp suspension exceeds, the flow becomes turbulent [57].

Benington et al[58] found that a pulp suspension acts as a non Newtonian fluid with a certain yield stress which is correlated to the volumetric concentration of the suspension and the type of pulp tested. Therefore, to design processes equipment used in pulp and paper industry the suspension yield stress has to be considered.

Duffy et al (1978) determined that a fluidized pulp suspension reduced turbulent drag below that of water alone in the same flow rate. They investigated the drag reduction characteristics of a pulp fiber suspension for different fiber concentrations, pipe diameters and pipe surface roughness. For different concentrations of wood pulp fiber, they found that high concentration has better drag reduction ability than lower concentration. They define the friction factor for the pipe.

\[
\Phi = \frac{\Delta P}{L} \cdot \frac{4D}{\rho U^2} \quad (2.4)
\]

Where,

\(\Delta P/L\) = longitudinal pressure gradient

\(D\) = pipe diameter

\(\rho\) = density of the suspending medium

\(U\) = bulk velocity
They found that drag reduction for water increased linearly with increasing bulk velocity. For pulp consistency, onset of drag reduction started and reached the maximum drag reduction asymptote while increasing the bulk velocity of the suspensions. Figure 2.1 showed that there are different asymptotes present. After the maximum drag reduction asymptote with increasing bulk velocity friction factor started to decrease but DR remains constant. They found that the ultimate level of DR is a function of fiber concentration and pulp type [59, 60].

2.5.1 The Phenomenon of Turbulent Drag Reduction with Respect to Pulp Suspensions

Duffy et al [60] gave an explanation about how pulp suspension reduces drag in a pipe flow. Inter fiber forces in between the fibers are of two types: chemical and mechanical. Mechanical entanglement of fiber produces flocs in the suspension. Momentum transfer of fiber is affected by the flocs in two opposing ways: (1) by damping the turbulence of the suspending medium these flocs decrease the small scale momentum transfer (2) by providing a solid link in between the adjacent layer of the suspension they increase the momentum transfer. Therefore, momentum transfer is dependent on the flocs size; the average flocs size will increase the tendency of making link in the adjacent fluid layer. Momentum transfer of the suspension is related to the local mean velocity gradient of the flow, when the momentum transfer is lower the mean velocity gradient is greater. For a particular pressure gradient the bulk flow rate increases with the increase of the local mean velocity gradient. This means that reducing the longitudinal pressure gradient for a particular flow rate will actually decrease the drag reduction.
2.6 Taylor-Couette Type Flow

Taylor couette flow has an important effect in the fundamental concept of fluid dynamics. Taylor G. I [61] had done ground breaking experiment to investigate the stability of couette flow when the inner cylinder is rotating and the outer cylinder is fixed. The Reynolds number for Taylor couette flow is:

\[ R_e = \frac{\omega r_1 (r_2 - r_1)}{v} \]  

(2.4)

Where,

\( \omega \) is the angular velocity of the inner cylinder,

\( r_1 \) and \( r_2 \) are the radius of inner and outer cylinder ,

\( v \) is the kinematic viscosity of the fluid.

After a certain Reynolds number the flow becomes unstable and there appear vortices known as Taylor vortices. The annulus between the two cylinders get filled by these vortices. The axes of these vortices are located along the circumference and they rotate in alternating opposite directions [37]. In the pulp and paper industry the screening equipment use the concept of Taylor couette flow.

We have previously mentioned about the experiment of Benington et al [58], where they used two instruments to measure the yield stress of the pulp fibers. One was a viscometer and the other a concentric cylinder rotary shear tester, the principal of these devices lies in Taylor couette flow. Both of these instruments were consisting of a housing having baffles arranged 60 degree intervals around the periphery. The minimum gap width between the housing and the rotor was 20mm.

The power consumption for turbulent or fluidized semi-bleached kraft softwood pulp was determined by using two concentric cylinders [62]. In the experimental setup a couette type flow
was generated by a rotor and housing, the gap size between the rotor and housing was varied between 65 and 5mm. In the housing and rotor, there were six vanes or baffles. Recently, [58] researchers have established that in a rotary device when the rotational speed increased a growing cavity of pulp is formed having a large tangential motion bounded by stationary pulp. This regime is somewhat like mixed regime of pipe flow. Whereas, the outer stationary plug of pulp corresponds to the plug flow regime in pipe flow. The size of the pulp cavity was increased by increasing the rotor speed until the cavity grows to some extent to touch the outer cylinder. When the cavity reached the van of the outer cylinder the flow turned to turbulent flow as a consequence of the interactions between the flow and the vans [57, 63]. A rotary shear tester was considered as a mixer to substantiate that the pulp flow behaved as a fluid in a turbulent regime. The mixer was characterized by a power number-Reynolds number relationship. At a high Reynolds number, Power number is independent of Re, while the flow becomes turbulent [58, 62]. Since the power numbers for pulp suspension in the fluidized region and for water in the turbulent region were found to be similar, pulp suspension in a concentric cylinder behaves as a turbulent viscous fluid.

2.7 Research Objective

It has been shown in the literature that a little amount of polymer additive in a turbulent flow can reduce turbulent drag in a large amount. However, the exact mechanism of polymer drag reduction is not well understood. It has also seen from the literature that the power consumption of the screen is dependent on the rotor tip speed. As, drag reduction by riblets vary up to $s^+ \leq 30$, effect of DR can be seen at $s^+ \approx 30$. Drag reduction combined with riblet and polymer is higher than each technique alone. If any effect can be found, while using riblet, polymer and pulp combining in a rotary device. The general goal of this research is to obtain turbulent drag by
addition of polymer additives in low consistency pulp suspension. The specific objectives of this thesis are to:

1. Experimentally determine the effect of polymer additives with low pulp concentration in pressure screen.
2. Design a rotor having microstructure (ribs) to find out microstructure element has any influence in drag reduction.
4. Experimentally finding a method for large-scale power saving in industrial application.
5. Experimentally determine the effect of polymer additives and riblets for turbulent drag reduction in presence of pulp.
Chapter 3 Experimental Setup

3.1 Introduction

The flow in the neighborhood of a rotating disk is of great interest to the researcher, particularly in connection to a rotary machine. In the paper industry, a semi-dilute suspension of pulp fiber is processed through different channels and devices before forming the final product. Some of the processing device include:

- Pressure screening
- Head box
- Hydro cyclone
- Refiner

Figure 3.1 Summary of papermaking unit operation

Figure 3.1 shows some of the unit operation during papermaking. The most efficient way of removing contaminates from pulp suspension thereby improving the strength, smoothness and optical quality of paper is to use Pressure screens. Pulp and contaminates enter the screen
through the feed port and pass over the rock trap, which prevents large debris from entering and
damaging the screen and rotor. The pulp flows down between the screen plate and the rotor. The
pulp fibres preferentially pass through the screen plate and out through the accept port. The
remaining fiber with debrises continues down the feed side of the screen plate and goes out of
the reject port.

Previous studies have shown that the riblet surface aligned in the stream wise direction reduce
turbulent skin friction. Drag reduction study with polymer solution has been done in a wide
range with pipe flow. Some drag reduction study with disk geometry is seen recent time.

3.2 Experimental Setup

Rotor power and capacity study was conducted using a laboratory Multi Rotor 8(MR8) pressure
screen at pulp and paper center of the University Of British Columbia, as shown in figure 3.1. A
detailed description of the facility can be found in previous studies [64]. MR-8 is 8 in (20.32cm)
in diameter (housing) and is equipped with a variable frequency drive (VFD) which controls the
rotor speed and power measurements. Magnetic flow meters are equipped on accept and reject
lines of the pressure screen to measure the flow rate. There are pressure sensors on the feed as
well as accept and reject pipes.
A 1000L stock tank is connected with the device through a pump to feed the MR-8. During the screening processes the accept and the reject streams are recirculating back into the stock tank. In the experiment a fixed cylinder was used instead of the pressure screen, which allows only feed and reject flow in the system. Which implies that feed flow rate is equal to the reject flow rate.
Figure 3.3 A modern pressure screen [5].
3.3 Rotors

Three different type rotors geometry were used during experiments.

Table 3.1: Rotor parameter

<table>
<thead>
<tr>
<th>Rotor type</th>
<th>Plane</th>
<th>Ribs</th>
<th>EP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.127 m</td>
<td>0.127 m</td>
<td>0.1842 m</td>
</tr>
<tr>
<td>Rib height</td>
<td></td>
<td>1.15mm</td>
<td></td>
</tr>
<tr>
<td>Rib thickness</td>
<td></td>
<td>0.5mm</td>
<td></td>
</tr>
<tr>
<td>Rib spacing</td>
<td></td>
<td>2.3mm</td>
<td></td>
</tr>
</tbody>
</table>

| Housing    |       |       |       |
| Diameter   | 0.203 m | 0.203 m | 0.203m |
| Gap width  | 38 mm   | 38mm   | 9.4 mm |

Figure 3.4 Plane rotor inside the housing
In our experiment we computed $s^+ = 30$, for very low tip speed of 0.3325 m/s with skin friction 0.003 for Re number $4.22 \times 10^4$. Figure 3.4. shows the rib rotor with longitudinal riblets. Detail geometry of riblet is also given. The radius ratio of outer and inner cylinder is greater than 1.5 [65].

![Figure 3.5 Ribs rotor](image-url)
The rotor in the MR8 is driven by a motor that is connected with the DAQ (computer). Rotating speed of the rotor can control directly by VFD or from labview program. However, the rotor in
the MR8 pressure screen does not always run exactly the same speed of the motor due to the different load from the fluid. Therefore, there is small deflection at small load while big deflection at high load. It is important to record the real rotating speed and torque of the rotor during the experiments. A pulley torque meter MCRT® 3120TA by S. Himmelstein and Company was used to measure the torque generated by the rotor in the shaft. This pulley torque meter is connected with the shaft of the pressure screen. The accuracy for speed of this sensor is ±0.05 and the accuracy of torque is ±0.1 for full scale (50 lbf-in). The PC interface cable of the sensor is connected with the DAQ.

Figure 3.8 Pulley torque sensor
3.5 Experimental Procedure and Plan

3.5.1 Procedure

The relation between power and torque is very simple

\[ P = \tau \omega \]  

(3.1)

Where,

\( P \) = power,

\( \tau \) = torque,

\( \omega \) = angular speed

By using the above equation, power generated by the fluid on rotor can be measured easily. A Labview program, which was previously prepared (Sean Delfel)[64] to record all measured data to text files. Rotor speed was increased from 200 rpm to 1600rpm with an increment of 100rpm. This program consists of four main Parts: (1) experimental conditions include the basic information of the flow rate, feed and reject pressure and the rotating speed of the rotors (2) Control of the frequency of the pump (3) experimental output converted to power. In one minute this system can save 60,000 data points. For data analysis, the average value of power and speed were calculated from the collected data per minute. For each rotor type, the power exerted by the fluid was measured for a large range of rotating speed, starting from lower speed to higher speed. Therefore, the highest rotor speed was around 1600rpm for water, pulp, polymer and pulp with polymer. For the polymer test three flow rate were run one after another continuously from lowest to highest flow rates. One single flow rate takes upto 20minutes while running at speeds of 200-1600 rpm with the interval of 100 rpm. The torque sensor can read data for every millisecond; data was recorded for one minute for a single rpm and the mean of that particular
rpm and power was obtained. Therefore, it took 1 hour to process the data for three flow rates from lower to higher flow rates respectively. After that, the polymer degradation was measured by running the pump in the same rpm range for one of the previous measured flow rates for 16-20 minutes. If for the repeated flow rate data matches to the previous calculated data, there is no degradation.

Figure 3.9 Data collection processes

Every day before the fluid test, the shaft power was measured without any fluid in pressure screen in the test speed condition, which is called air power. The mechanical error due to seal and bearing of the shaft as well as power taken by the motor was eliminating from the total rotor power by subtracting the air power for each speed.
A series of experiments were done to investigate the effects of surface contour modification on the rotor power consumption. A-PAM polymer was used during the experiment to find the effect of polymer drag reduction on rotor power consumption. In particular, the following tests were run during the experiments:

### Table 3.2: Trial protocol

<table>
<thead>
<tr>
<th>Series</th>
<th>A-PAM</th>
<th>Pulp (mass%)</th>
<th>RPM</th>
<th>Q (flow rates)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>200:1600</td>
<td>114, 227,455 l/min</td>
</tr>
<tr>
<td>2</td>
<td>20,50,100,200ppm</td>
<td>0</td>
<td>200:1600</td>
<td>114,227,455 l/min</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1,2</td>
<td>200:1600</td>
<td>114,227,455 l/min</td>
</tr>
<tr>
<td>4</td>
<td>20,50,100,200ppm</td>
<td>1</td>
<td>200:1600</td>
<td>114,227,455 l/min</td>
</tr>
<tr>
<td>5</td>
<td>20,50,100,200ppm</td>
<td>2</td>
<td>200:1600</td>
<td>114,227,455 l/min</td>
</tr>
</tbody>
</table>

#### 3.5.2 Solution Preparation

The experimental study was consisted of three sets of tests. First, the effect of pulp concentration in the Pressure screen was studied for three rotors. Dry bleached Kraft pulp (NBKP) from a British Columbia pulp mill was used in this experiment at three different mass concentrations of 0%, 1% and 2%. The measurement test of Pulp concentrations was performed before each test. During the test the feed flow rate of the pressure screen was changed from 114 l/min, 227 l/min and 455 l/min with a 20hp pump. All experiments were run at 20-30°C unless otherwise noted.
Table 3.3 Test condition used in set one

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Speed</td>
<td>200 rpm up to 1600rpm</td>
</tr>
<tr>
<td>Fluid</td>
<td>Water + Polymer at 20°C - 30°C</td>
</tr>
<tr>
<td>Polymer concentration</td>
<td>20ppm, 50ppm, 100ppm, 200ppm</td>
</tr>
<tr>
<td>Flow rates</td>
<td>30gpm, 60gpm, 120gpm</td>
</tr>
<tr>
<td>Average mixing time</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Average test time</td>
<td>1hour</td>
</tr>
</tbody>
</table>

The next set of tests investigated the drag reduction phenomena of polymer concentration on the pressure screen. Tap water was used as a reference fluid and temperature raised somewhat between 20°C to 30°C during the test. An anionic polymer from Kemira, with trade name: SUPERFLOC A-10 was used as polymer additive. Polymer solutions were first made in small buckets by using an overhead agitator for 6 to 7 hours at room temperature at low speed. Later this solution was added to the water of the main tank for accurate polymer concentration. Since temperature has an effect on polymer additives, during the experiment temperature raised in between 20-30°C. However, A-PAM looked like gel when it was dissolved in water. At low temperature, the gel formed faster and at high temperature this gel broke down.
Table 3.4 Test condition used in set two

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Speed</td>
<td>200 rpm up to 1600rpm</td>
</tr>
<tr>
<td>Fluid</td>
<td>Water + Polymer at 20°c -30°c</td>
</tr>
<tr>
<td>Polymer concentration</td>
<td>20ppm, 50ppm, 100ppm, 200ppm</td>
</tr>
<tr>
<td>Flow rates</td>
<td>30gpm, 60gpm, 120gpm</td>
</tr>
<tr>
<td>Average mixing time</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Average test time</td>
<td>1hour</td>
</tr>
</tbody>
</table>

In the third set of tests, the combined effect of pulp and polymer additives in DR on Pressure screen was studied. Pulp concentrations were prepared first and diluted polymer solution added in the test tank later. Polymer solutions were prepared in the same way as test condition used in set two.
Table 3.5 Test condition used in set three

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Speed</td>
<td>200 rpm up to 1600rpm</td>
</tr>
<tr>
<td>Fluid</td>
<td>Water + Pulp +Polymer at 20°c -30°c</td>
</tr>
<tr>
<td>Polymer concentration</td>
<td>20ppm, 50ppm, 100ppm, 200ppm</td>
</tr>
<tr>
<td>Flow rates</td>
<td>114 l/min, 227 l/min, 455l/min</td>
</tr>
<tr>
<td>Average mixing time</td>
<td>1-2 hours</td>
</tr>
<tr>
<td>Average test time</td>
<td>1hour</td>
</tr>
</tbody>
</table>

3.5.3 **Life Expectance of Polymer**

As polymer degrades when pass through a pump facility, a rheological test was performed to obtain the degradation of polymer. Rheological test were performed by rheometer Kinexus from Malvern with cone and plate geometry and with a diameter of 40mm, 1° cone angle. Shear rate ramp test was performed for polymer in water solution, by increasing the shear rate with time in linear fashion. Temperature control is provided by the system and accurate to 1°C.
Figure 3.10 Shear stress vs shear rate for 20ppm A-PAM

As shown in Figure 3.10, that polymer shear stress remained same while increasing the share rate after and before the test, which indicates that polymer was not degraded during the test. For a pulp and polymer combined solution the degradation measurements were done by repeating the rpm vs power test for the particular rotor in the highest flow rate after completing the test with three existing flow rates.
Figure 3.11: Power number vs Reynolds number for 100ppm A-PAM with 2% pulp in plane rotor.

Figure 3.12: Power number vs Reynolds number for 20ppm A-PAM with 2% pulp in EP rotor.
Figure 3.11 shows that at higher rpm for 100 ppm A-PAM with 2% pulp plane rotor used almost same power in second time running as first time running. This also proves that the polymer in the combined mixture of pulp and polymer had not degraded yet. Whereas in figure 3.12, EP with 20ppm A-PAM and 2% pulp used higher power in the second run than the first run over all speed range. This indicates, with industrial rotor polymer degraded in a faster rate.
Chapter 4  Experimental Results and Discussions

4.1  Introduction

The power on the rotor while running in the MR8 was obtained for a wide range of design and operating variables, including rotational velocity, rotor diameter, rotor type and fluid type. The experimental results are categorized into three groups namely plane rotor, Ribs rotor and EP (industrial rotor). Tap water was used as the reference fluid. During the experiment, the feed flow rate was increased from lowest to highest.

4.2  Data Analysis

In the previous study, Chad and Richard experimentally found that pulp flow behavior as a fluid in turbulent regime can explained by Non-dimensional parameter power number[62, 66], which is defined as:

\[ N_p = \frac{P}{V_t^3 \rho D^5} \]  \hspace{1cm} (3.2)

Where, \( P \) is the power on the rotor,
\( \rho \) is the fluid density,
\( \mu \) is the dynamic viscosity of the fluid,
\( D \) is the diameter of the rotor,
\( V_t \) is the rotor tip speed.
Reynolds number is based on the rotor diameter and is defined as:

\[
\text{Re} = \frac{\rho \omega r^2}{\mu}
\]  

(3.3)

Where, \( \rho \) is the density of the fluid,

\( \omega \) is the angular velocity of the rotor,

\( r \) is the radius of the rotor,

\( \mu \) is the dynamic viscosity of the fluid

In the data analysis processes, water dynamic viscosity was used for all conditions tested in order to maintain the same test condition.

**4.3 Smooth Rotor**

**4.3.1 Effect of Polymer Concentration**

Effects of polymer concentrations over 0%, 1% and 2% pulp are shown for rotational speeds of 200-1600rpm. For a smooth rotor with 1% pulp and 50ppm A-PAM shows better results at 455l/min flow rates. Figure 4.1 shows power number vs Reynolds number for 1%pulp, water, 50ppm A-PAM and 1% pulp with 50ppm A-PAM at 455 l/min flow rate. It is interesting to note that the power measured for pulp with polymer is at the lower detection limit of the device. The difference between the power obtained by pulp and the power obtained by water in low rpm is huge. The power number is independent of Re at higher Re [62]. The curves shown in the figure are similar to those found in other mixer. Three regimes are present in this curve: at low Re a laminar regime, a transition region and a turbulent regime. Since the flow becomes turbulent at higher tip speeds, DR or power saving graphs were generated above 6 m/s tip speeds. From the Figure 4.1 it is distinguishable, that turbulent regime starts from Re \( 2.5 \times 10^4 \) [62], where power number is independent of Re number at high Re number.
Figure 4.1 Nondimensional power number vs. Reynolds number for 1% pulp with 455 l/min feed flow

A-PAM is a shear-thinning fluid, which means the viscosity decreases with shear rate or shear stress decreases with shear rate. A-PAM solution alone takes less power than water.

4.3.2 Power Saving

The power saving or Drag reduction was obtained by first measuring the power required to rotate the rotor at a given speed in the pulp solution. By measuring the corresponding power required to maintain the same speed in the solvent with added polymer and the power saving equation is as follow [15, 67, 68]

\[
\text{Power Saving} = \frac{P_{n,pulp} - P_{n,pulp+polymer}}{P_{n,pulp}} 
\]

(4.1)
However, mechanical power generated \((P_{nm})\) from the bearing which supports the shaft and rotor is also considered, more accurate equation for power saving becomes

\[
\text{Power Saving} = \frac{(P_{n,pulp} - P_{nm}) - (P_{n,pulp+polymer} - P_{nm})}{(P_{n,pulp} - P_{nm})}
\]

(4.2)

Power saving at feed flow rates of 141 l/min, 227 l/min and 455 l/min for tip speeds of 6.66 m/s to 10.66 m/s are shown in figure 4.2, as in this region flows become turbulent.

The effect of varying tip speeds on the power saving is shown in figure 4.2. There are clear trends of decreasing of power saving with increasing tip speed. At tip speed 10.6 m/s (\(\text{Re} 4.29 \times 10^4\)) power saving reaches to 81\% ± 3\% for feed flow rate of 455 l/min. Consequently,
for feed flow rate of 114 l/min Power saving diminishes from 94% ± 3% to 56% ± 2.2% for tip speed 8.6 m/s to 10.6 m/s respectively. As can be seen for medium flow rate 227 l/min the Power saving is almost horizontal and fluctuate a lot. Even so, Power saving for 227 l/min is 70%±7.5% at Re $4.29 \times 10^4$ (10.6 m/s).

Figure 4.3 shows the effect of polymer on Power saving for 50ppm A-PAM and 1% consistency pulp in medium or 227 l/min flow rate. Power saving decreases from 78%±8.4% at tip speed of 6.67 m/s to 70%±7.5% at tip speed 10.6 m/s (Re $4.29 \times 10^4$).
Figure 4.4 Power saving vs Reynolds number for 114 l/min, 227 l/min, 455 l/min at 100ppm A-PAM with 1% pulp consistency

No Drag reduction can be seen in figure 4.4 before Re $3.5 \times 10^4$ for 114 l/min and 227 l/min flow rate. After that DR or Power saving starts to increases and at Re $4.29 \times 10^4$ Power saving reaches 36%±3.6% for 227 l/min flow rate. Overall, little Power saving is observed for 114 l/min flow rates. In fact at tip speeds of 10.6m/s (Re $4.29 \times 10^4$) Power saving is 16%±0.52% for 114 l/min flow rate. However, for a flow rate of 455 l/min Power saving decreases with increasing Re number and reaches to 40%±1.2% for higher Re number $4.29 \times 10^4$. 
Figure 4.5 power saving vs Reynolds number for 114 l/min, 227 l/min, 455l/min for 200ppm A-PAM with 1% pulp consistency

Figure 4.5 shows 30-42% Power saving at higher Re number. As can be seen for a medium flow rate 227l/min Power saving fluctuates more than other flow rates. It is evident that, higher Power saving is found for 1% pulp concentration when A-PAM dosages of less than 100ppm.
Figure 4.6 Power saving vs Reynolds number for 114 l/min, 227 l/min, 455 l/min for 20ppm A-PAM with 2% pulp concentration

Figure 4.7 Power saving vs Reynolds number for 114 l/min, 227 l/min, 455 l/min for 50ppm A-PAM with 2% pulp concentration
In Figure 4.6, 4.7 and 4.8 it can be seen that for 2% pulp consistency with different A-PAM concentration Power saving starts to increase with increasing polymer concentration and at 50ppm A-PAM it reaches maximum limit. After that Power saving decreases with increasing polymer concentrations. These also indicate that at a certain polymer concentration Power saving is maximum. Moreover, the maximum power saving of 74%± 2.3% occurred at Re 4.29×10^4 with 50ppm A-PAM with 2% pulp concentration for 455l/min feed flow rate.

4.3.3 Summary of Plane Rotor Results

The effect of varying polymer concentration of plane rotor at constant flow rate can be clearly seen. The tip speed was varied from \( V_t = 6.7 \text{ m/s} \) to \( V_t = 10.6 \text{ m/s} \). DR or power saving starts
to increase with increasing polymer concentration and after reaching its optimal polymer concentration power saving starts to decrease.

Table 4.1 Summary of plane rotor results

<table>
<thead>
<tr>
<th>A-PAM</th>
<th>Pulp</th>
<th>Flow rate</th>
<th>Tip speed</th>
<th>Re</th>
<th>Power Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>56%±2.2%</td>
</tr>
<tr>
<td>20</td>
<td>1%</td>
<td>227</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>70%±7.5%</td>
</tr>
<tr>
<td>20</td>
<td>1%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>81%±3%</td>
</tr>
<tr>
<td>50</td>
<td>1%</td>
<td>227</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>70%±7.5%</td>
</tr>
<tr>
<td>100</td>
<td>1%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>16%±.52%</td>
</tr>
<tr>
<td>100</td>
<td>1%</td>
<td>227</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>36%±3.6%</td>
</tr>
<tr>
<td>100</td>
<td>1%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>40%±1.2%</td>
</tr>
<tr>
<td>200</td>
<td>1%</td>
<td>227</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>52%±5.6%</td>
</tr>
<tr>
<td>200</td>
<td>1%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>31%±1%</td>
</tr>
<tr>
<td>20</td>
<td>2%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>38%±1.1%</td>
</tr>
<tr>
<td>20</td>
<td>2%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>50%±1%</td>
</tr>
<tr>
<td>50</td>
<td>2%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>71%±2%</td>
</tr>
<tr>
<td>50</td>
<td>2%</td>
<td>227</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>66%±5</td>
</tr>
<tr>
<td>50</td>
<td>2%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>69%±2%</td>
</tr>
<tr>
<td>100</td>
<td>2%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>47%±2.5%</td>
</tr>
<tr>
<td>100</td>
<td>2%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10⁴</td>
<td>47%±2.5%</td>
</tr>
</tbody>
</table>

Table 4.1 shows summary of plane rotor results. Addition of A-PAM shows drag reduction phenomena for all condition tested. Larger effects were found for lower pulp concentrations, APAM dosages of less than 100 ppm, which indicates that drag reduction phenomena increases with polymer concentrations and there is an optimum polymer concentration at which maximum DR or power saving occurs. Optimal polymer concentration of plane rotor for 1% and 2% pulp concentrations is 50-ppm A-PAM. Overall Power saving range is 20-60%.

The effect of varying the flow rates on DR or Power saving is observed for both 1% and 2% pulp with polymer concentrations. As mentioned previously higher flow rate contained less power
than lower flow rate. At higher tip speeds, the clear trends of DR or Power saving are seen. Power saving is higher for higher flow rates than that for lower flow rates.

4.4 Ribs Rotor

4.4.1 Effect of Polymer Concentration

Ribs rotor was tested during the experiment under the same condition as that of the smooth rotor. In this section, the effect of ribs and fluid types on power requirement is examined. Non-dimensional analysis is done to establish correlation among the variables. Experiments were done in a wide range of tip speeds, but only Power saving of higher tip speed was discussed in Power saving section because at higher tip speeds flow becomes turbulent. Experimental results showed riblet have great influence on the rotor power consumption. At higher Re number the difference among Power number for water, pulp, polymer and pulp with polymer is hardly seen. For all the flow rates tested during the experiments the trend of Power number vs Re number is similar to Figure 4.9. It is seen from Figure 4.9 that Power number for polymer alone and pulp with polymer is at the lower level of machine detection limit. It is noticeable that the measured power increased nonlinearly with the rotating speed and ribs has relatively slight influence on power.
Figure 4.9 Nondimensional power number vs. Reynolds number for 1% pulp with 117 l/min feed flow rate

### 4.4.2 Power Saving

Power saving of a ribs rotor is measured by using equation 4.2. Power saving for ribs rotor with 1% and 2% consistency of pulp with polymer concentration over 114 l/min and 455 l/min feed flow rate is discussed in this section. At highest tip speed, flow becomes laminar to turbulent; we consider seven tip-speeds from 6.67 to 10.67 m/s. The combined effect of pulp and polymer in DR is discussed for rib rotor. The effect of polymer concentration and effect of flow rate over riblet geometry in DR is observed. As can be seen in Figure 4.10 drag reduction for flow rate 455 l/min start decreasing from 81%±3% to 65%±2% at Re 2.95×10^4 to Re 4.29×10^4 respectively.
Figure 4.10 Power saving vs Reynolds number for 20 ppm polymer concentration with 1% consistency pulp.

Figure 4.11 Power saving vs Reynolds number for 50ppm -PAM with 1% consistency pulp.
Figure 4.12 Power saving vs Reynolds number for 100ppm -PAM with 1% consistency pulp

Figure 4.13 Power saving vs Reynolds number for 200ppm -PAM with 1% consistency pulp
The effect of varying polymer concentration is more clearly seen in Figures 4.10-4.13. Power savings or DR increases most at 100ppm polymer with pulp concentration and after that with increasing polymer concentration Power saving decreases. Overall, Power saving is observed for all polymer concentrations tested. Figure 4.12 indicates maximum power saving of 66%±2.3% for 100ppm A-PAM at highest Re $4.29 \times 10^4$. There are clear trends of decreasing Power saving with increasing Re number. The shear stress is higher at higher tip speed, which has an effect on pulp and polymer network structure. With increasing Re number power saving starts to decline at all polymer concentrations. This indicates to the fact that the polymer does not degrade during the experiment. If polymer degrades than no Power saving could found in higher flow rates, as during the experiment flow rate was changing from lower to higher.

![Graph](image)

Figure 4.14 Power saving vs Reynolds number for 20ppm –PAM with 2% consistency pulp
Figure 4.15 Power saving vs Reynolds number for 50ppm –PAM with 2% consistency pulp

Figure 4.16 Power saving vs Reynolds number for 100ppm –PAM with 2% consistency pulp
Figure 4.17 Power saving vs Reynolds number for 200ppm –PAM with 2% consistency pulp

It is evident that from Figure 4.14-4.17 that for 2% pulp consistency with a constant polymer concentrations Power saving is higher at high flow rates than low flow rates. However, 100ppm A-Pam with 2% consistency pulp for feed flow rate 455 l/min maximum Power saving is 93%±3.4% at Re $4.29 \times 10^4$.

### 4.4.3 Summary of Ribs Rotor Results

Addition of polymer shows drag reduction effect in all conditions tested. The effect of varying flow rate over Power saving is seen for both 1% and 2% pulp with different polymer concentration. The general trend of DR over different flow rate is showed above, which decreases linearly with increasing Re number. At higher tip speeds a clear trend is seen for all pulp and polymer concentrations.
Table 4.2 Summary of ribs rotor results

<table>
<thead>
<tr>
<th>A-PAM</th>
<th>Pulp</th>
<th>Flow rate</th>
<th>Tip speed</th>
<th>Re</th>
<th>Power Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>69%±2.2%</td>
</tr>
<tr>
<td>20</td>
<td>1%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>65%±2%</td>
</tr>
<tr>
<td>50</td>
<td>1%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>30%±0.9%</td>
</tr>
<tr>
<td>50</td>
<td>1%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>38%±1.1%</td>
</tr>
<tr>
<td>100</td>
<td>1%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>62%±2.2%</td>
</tr>
<tr>
<td>100</td>
<td>1%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>67%±2.3%</td>
</tr>
<tr>
<td>200</td>
<td>1%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>34%±1.1%</td>
</tr>
<tr>
<td>200</td>
<td>1%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>58%±1.9%</td>
</tr>
<tr>
<td>20</td>
<td>2%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>37%±1.2%</td>
</tr>
<tr>
<td>20</td>
<td>2%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>30%±0.9%</td>
</tr>
<tr>
<td>50</td>
<td>2%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>49%±1.5%</td>
</tr>
<tr>
<td>50</td>
<td>2%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>66%±1.5%</td>
</tr>
<tr>
<td>100</td>
<td>2%</td>
<td>114</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>42%±1.4%</td>
</tr>
<tr>
<td>100</td>
<td>2%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>93%±3.5%</td>
</tr>
<tr>
<td>200</td>
<td>2%</td>
<td>144</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>2%</td>
<td>455</td>
<td>10.6</td>
<td>4.29 × 10^4</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.2 shows the summary of ribs rotor results. Figure 4.16 shows highest Power saving for 455l/min flow rates among all the condition tested. For instance, after Re 3.47×10^4 power saving for both the flow rates level off. However, for 114 l/min flow rate maximum power saving of 62%±2.2% occurred at highest tip speed 10.6 m/s(Re 4.29×10^4) with 1% consistency pulp and 100ppm A-PAM. Moreover, Power saving of rib rotor is higher than the plane rotor.

Effects of pulp consistency over power saving were observed for ribs rotor. 1% consistency pulp with 100ppm A-PAM shows highest DR or power saving for 114 l/min flow rate. On the contrary, 2% pulp with 100 ppm A-PAM showed highest DR effect for 455l/min flow rates. This bring the matter to a conclusion that optimum pulp consistency lies between 1-2% pulps where the DR or Power saving is highest.
4.5 EP Rotor

4.5.1 Effect of Polymer Concentration

Power saving of Industrial rotor is measured in the same way as the smooth and the ribs rotor. The diameter of EP rotor is higher than smooth and ribs rotor, which changes the Reynolds number range as well as range of Non-dimensional Power number.

Figure 4.18 Nondimensional power number vs. Reynolds number for 1% pulp with 114 l/min feed flow rate

Figure 4.18 shows that 1% consistency pulp with EP rotor takes significantly higher power than that of water at low tip speeds. A-PAM alone and A-PAM with pulp takes such a low power, which is at the lowest point of machine detection limit.

4.5.2 Power Saving

To measure the power saving or DR for combined flow of pulp and polymer in EP rotor with that over pulp, equation 4.2 is used. The tip speed of the rotor was varied from 6.7 m/s to 15.4 m/s.
As EP rotors are widely used in Paper industries, reduction of power consumption of EP rotor will minimize the production cost of paper.

![Graph showing power saving vs Reynolds number for 20ppm -PAM with 1% consistency pulp.](image)

Figure 4.19 Power saving vs Reynolds number for 20ppm -PAM with 1% consistency pulp
Figure 4.20 Power saving vs Reynolds number for 50ppm –PAM with 1% consistency pulp

Figure 4.21 Power saving vs Reynolds number for 100ppm A-PAM with 1% consistency pulp
Figure 4.22 Power saving vs Reynolds number for 200ppm A-PAM with 1% consistency pulp

Figure 4.23 Power saving vs Reynolds number for 20ppm A-PAM with 2% consistency pulp
Figure 4.24 Power saving vs Reynolds number for 50ppm A-PAM with 2% consistency pulp

Figure 4.25 Power saving vs Reynolds number for 100ppm A-PAM with 2% consistency pulp
4.5.3 Summary of EP Rotor

Power saving or DR of pulp and polymer over pulp is seen in all condition tested with 1% pulp consistency. The effect of varying tip speed is seen over 1% pulp with different polymer concentrations. The clear trend is that with increasing tip speed Power saving starts to decrease linearly. It is noticeable that, at tip speed $V_t = 7.72 \text{ m/s}$ the flow becomes turbulent where the drag reduction with 100ppm A-PAM with 1% pulp for 455 l/min is $86\% \pm 3\%$ and at higher tip speed of $V_t = 15.43 \text{ m/s}$ drag reduction drops to $38\% \pm 0.9\%$. Similarly, for 114 l/min flow rate power saving drops from $80\% \pm 3.1\%$ to $37\% \pm 1\%$ for tip speed of $7.72 \text{ m/s}$ and $14.48 \text{ m/s}$ respectively.

The effect of pulp concentration over DR or power saving is seen here, which indicate that Power saving is higher at 1% pulp than 2% pulp. At higher pulp concentrations with lower
polymer concentrations mechanical degradation of polymer is faster than higher polymer concentration, due to the fact that tip speed is higher in EP than other two rotors. To illustrate this point Figure 4.25 and Figure 4.26 show Power saving increase at 455 l/min flow rate for 20ppm and 200ppm A-PAM with 2% pulp respectively. At lower rotational speeds, 1% and 2% pulp suspension needs significantly more power than that of water.

Table 4.3 Summary of EP rotor

<table>
<thead>
<tr>
<th>A-PAM</th>
<th>Pulp</th>
<th>Flow rate l/min</th>
<th>Tip speed m/s</th>
<th>Re</th>
<th>Power Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1%</td>
<td>114</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>22%±0.6%</td>
</tr>
<tr>
<td>20</td>
<td>1%</td>
<td>455</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>24%±0.06%</td>
</tr>
<tr>
<td>50</td>
<td>1%</td>
<td>114</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>34%±0.08%</td>
</tr>
<tr>
<td>50</td>
<td>1%</td>
<td>455</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>33%±0.07%</td>
</tr>
<tr>
<td>100</td>
<td>1%</td>
<td>114</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>38%±0.09%</td>
</tr>
<tr>
<td>100</td>
<td>1%</td>
<td>455</td>
<td>14.5</td>
<td>$12 \times 10^4$</td>
<td>37%±0.1%</td>
</tr>
<tr>
<td>200</td>
<td>1%</td>
<td>114</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>1%</td>
<td>455</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>5.7%</td>
</tr>
<tr>
<td>20</td>
<td>2%</td>
<td>114</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>5% ± 0.01%</td>
</tr>
<tr>
<td>20</td>
<td>2%</td>
<td>455</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>9.3%</td>
</tr>
<tr>
<td>50</td>
<td>2%</td>
<td>114</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>2%</td>
<td>455</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>2%</td>
<td>114</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>2%</td>
<td>227</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>2%</td>
<td>455</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>11.1%±0.02%</td>
</tr>
<tr>
<td>200</td>
<td>2%</td>
<td>114</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>2%</td>
<td>227</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>2%</td>
<td>455</td>
<td>15.5</td>
<td>$13 \times 10^4$</td>
<td>8.8%±0.02%</td>
</tr>
</tbody>
</table>

Table 4.3 shows summary of EP rotor results. The effect of polymer concentration has an impact on flow rates in EP rotor with 1% consistency pulp. For lower polymer concentrations, Power saving is high at lower flow rates comparable to higher flow rates. The effect of flow rates over
power saving is seen in Figure 4.25. Power saving for \( V_t = 15.43 \text{ m/s} \) \((\text{Re} \ 413 \times 10^4)\) at high flow rates is slightly higher than low flow rates. With 2% pulp in higher polymer concentration of 200 ppm A-PAM for 455l/min flow rates showed 8.8\%+0.2\% DR for tip speed of \( V_t = 14.5 \text{ m/s} \). Similarly, with 2% pulp in higher polymer concentration of 100 ppm A-PAM for 455l/min flow rates showed 11.1\%+0.2\% DR for tip speed of \( V_t = 16.43 \text{ m/s} \). However, lower flow rate 114 l/min and 227 l/min shows drag increase for 2% pulp with different polymer concentration. Overall 20-80 \% drag reduction was seen for 1% pulp with polymer additives in the range of 20-200ppm A-PAM. At higher tip speeds for higher pulp concentrations the network between pulp and polymer additive became weak, this diminished polymer DR or Power saving effect. Power saving increased most at 100ppm A-PAM with 1% pulp, whereas; with 2%pulp and 200ppm A-PAM showed Power saving only at flow rates of 455l/min. At lower polymer concentrations with 2% pulp there was almost no Power savings because of the fact that with high shear stress the polymer degrades faster at low concentrations. It can be due to the fact that, at higher pulp consistency with lower polymer concentrations for EP rotor the network between pulp and polymer is weak. This bring the matter to a conclusion, for EP rotor the optimal pulp consistency lies between 1-2\%. As the tip speeds of the EP rotor were higher compared to the other two rotors, it may influence the polymer to degrade at a faster rate.
4.6 Effect of Polymer Over Riblets

Figure 4.27 Power number vs Reynolds number for 1% pulp with 100ppm A-PAM.

Figure 4.28 Power number vs Reynolds number for 2% pulp with 100ppm A-PAM.
Figure 4.27 and 4.28 show the difference of power number for plane rotor and ribs rotor in the presence of water, pulp suspension, polymer and combination of pulp and polymer. The hollow sign indicates for plane rotor whereas solid sign indicates ribs rotor. From Figure 4.1 and 4.9 it is observed that in presence of pulp alone ribs rotor takes more power than plane rotor. Whereas the addition of polymer shows significant amount of power reduction for ribs rotor over plane rotor. Literature suggests that at higher polymer concentration degradation of polymer with rib surface is less compare to plane surface. This incident is observed only for high concentration of polymer with pulp suspension.

Figure 4.29 shows non-dimensional power number for plane and ribs rotor under different test conditions during the experiment. Ribs rotor uses more power compared to plane rotor while running in water and pulp suspension. However, ribs rotor power consumption is lower
compared to the plane rotor while running with 100ppm polymer alone and 100ppm polymer with pulp suspension. Partly synergistic effect of ribs with polymer is seen, this phenomena is seen while rib rotor is running with high concentration polymer only.
Chapter 5  Summary and Conclusion

Pressure screening is an important process in the manufacture of high quality pulp and paper. It removes contaminants from the pulp stream, improves the smoothness, strength and optical quality of the paper sheet. The objective of this thesis was to determine experimentally the effect of rotor surface contours and polymer additives and pulp concentration on the power consumed during pressure screening.

Drag reduction (DR) or power savings were observed for all conditions tested throughout the experiments. Because of the fact that higher flow rates take less power than lower flow rate with any fluid solution in MR8 [64], DR or power saving is higher at high flow rates. In case of plane rotor, DR or power saving varies with pulp consistency as well as with polymer concentration. At higher rotating speeds, pulp with polymer solution becomes fully turbulent and decreases the power consumption of the rotor than that with water, this phenomenon is recognized as turbulent drag reduction. A plane rotor uses less power compare to a ribs rotor with the same tip speeds. The addition of A-PAM to pulp suspensions provides drag reduction for all conditions tested. Drag reduction was found to increases with polymer concentration up to maximum at the optimum polymer concentration.

The detailed geometry or structure of the ribs rotor is given in chapter 3. The riblets increased the drag on the rotor resulting in higher power consumption. The dimensions of the drag reducing riblets are as small as the viscous sublayer, which causes technological difficulties to manufacture these devices. The presence of the riblets increases the wetted perimeter of the rotor surface increasing drag and power consumption. DR or power saving occurred in all conditions.
tested and the maximum drag reduction of 93%±3.4% has seen for 100ppm A-Pam with 2% consistency pulp for feed flow rate 455l/min at Re number $4.29 \times 10^4$. Partially synergistic effect for higher concentration of polymer is observed.

The power number of an industrial EP rotor is less than the plane and ribs rotors, due to the geometrical shape. Moreover, 1% pulp with polymer additives has modest DR effect over that with 2% pulp with polymer concentration. At higher pulp and polymer concentrations, power saving was observed only for higher flow rates of 455 l/min. All the rotors including EP rotor showed that Power saving increased with the increasing flow rates.

In summary, polymer additives have a great influence on power saving with various pulp consistencies. For industrial rotors the optimal polymer and pulp concentration is, 100ppm A-PAM with 1% consistency pulp. There is an optimal pulp concentration between 1% and 2% for all three rotors where the drag reduction is maximum.
Chapter 6 Future Work

In order to reduce power consumption in screening processes, beyond the work of this thesis, researchers should conduct further experiments on drag reduction with pulp, polymer and with ribs to achieve a better understanding of the mechanisms. This thesis found that at higher flow rates power savings are higher compared to lower flow rates with pulp and polymer concentrations. For 227 l/min feed flow rates power saving results were fluctuating which were sometimes lower than the lowest flow rate. Therefore, further tests can be done for a wide range of flow rates. There is an optimal pulp consistency in between 1% and 2% pulp consistency where power savings are the highest. This thesis only used 1% and 2% pulp consistency, future tests can be done to find out the optimal pulp consistency. This thesis found that riblets have an effect on power savings if used with pulp concentrations in addition of polymer. Riblets on EP rotor can be designed and used for screening process with polymer concentrations to find their effects when combined with polymers.
References


Appendix

1. Error analysis by standard normal

\[
\frac{a_o (\pm a_1) - b_o (\pm b_1)}{c_o (\pm c_1) - d_o (\pm d_1)} = x \pm x \sqrt{\left(\frac{a_1}{a_o}\right)^2 + \left(\frac{b_1}{b_o}\right)^2 + \left(\frac{c_1}{c_o}\right)^2 + \left(\frac{d_1}{d_o}\right)^2}
\]

2. MR8 test facilities