FORMULATION OF NATURAL DRAG-REDUCING AGENT FROM MALABAR SPINACH FOR AQUEOUS LIQUID FLOWING IN TURBULENT MODE THROUGH PIPELINES

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ABSTRACT

In this study, the drag-reducing properties of mucilage extracted from the stem of the Malabar spinach in both aqueous liquids flowing in pipelines are investigated. Fluid flowing in turbulent through pipelines produce pressure drop as a result of friction resistance. Pumps are installed to reduce pressure drop; however this increases the costs of the pipeline system. Conventional drag-reducing agents include polymers, suspended solids and surfactants. Mucilage is a new member to this class of additives and has great potential as it is natural, cost-effective and biodegradable. An experimental piping rig was used to study the effects of Reynolds number, pipe length and mucilage concentration on drag reduction in water. The relationship between these factors and DR are discussed. The study shows that the maximum DR recorded was 78.2% at 300ppm concentration with internal pipe diameter of 0.0254m.

ABSTRAK

Dalam kajian ini, sifat bendalir yang diekstrak dari batang bayam Malabar untuk mengurangkan rintangan dalam cecair akueous yang mengalir di dalam paip disiasat. Cecair yang mengalir dalam mod bergelora melalui rangkaian paip mengalami susutan tekanan sebagai hasil rintangan geseran. Pam digunakan untuk mengatasi susutan tekanan tersebut; namun tindakan berikut menaikkan kos sistem paip. Agen pengurang *drag* yang konvensional termasuk polimer, pepejal tersuspensi dan surfaktan. Bendalir adalah ahli baru pada kumpulan ini dan mempunyai potensi hebat kerana sifat bendalir yang semulajadi, menjimat kos dan boleh dibiodegradasikan. Sebuah rig paip eksperimental digunakan untuk mengkaji kesan nombor Reynolds, kepanjangan paip dan kepekatan bendalir ke atas pengurangan *drag* dalam air. Hubungan antara faktor-faktor tersebut dengan pengurangan *drag* dibincang. Kajian menunjukkan pengurangan drag yang maksimum adalah 78.2% pada kepekatan 300ppm dengan diameter dalaman paip 0.0254m.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF NOMENCLATURE

Re	Reynolds number
ρ	Density
v	Velocity
μ	Viscosity
g	Gravitational acceleration
D	Internal pipe diameter
DR	Drag reduction
DRA	Drag-reducing agents
L	Pipe length (length of testing section)
M	Mass of mucilage
[M]	Concentration of mucilage
ΔP_o	Pressure drop at mucilage concentration zero
ΔP_i	Pressure drop at mucilage concentration i
ppm	Parts per million
Q	Water flow rate
®	Registered trademark

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Pipelines are a prominent part in any chemical industry. It is an essential component to transport fluids, liquid and/or gas from one point to another. However, liquid flowing in turbulent mode through these pipelines experience drag which is indicated by pressure drop between two points. Pumps are installed to reduce the pressure drop but this leads to increased utility costs, not only for installation but also for maintenance. Today, pumping systems constitute 20% of the world's electrical energy demand and consumes 20-50% of the energy usage in certain industrial plant operations (Hydraulic Institute, 2001). Another factor is the energy crisis, where process plants focus on reducing power consumption by rotating equipment to curb increasing power costs (Sahoo & Guharoy, 2009).

Since turbulence is an inevitable property of liquids flowing in pipelines, there is a need to reduce the cost of pumping systems and the industry is looking at drag reduction (DR) for the solution. Research has shown a growing trend for drag-reducing agents which, when added to the flowing liquid in small quantities, can reduce drag at a less expensive cost. Typically polymers, suspended solids and surfactants are used as drag-reducing agents. However there is a need for drag-reducing agents from natural and easily available sources; environmental consciousness also expands this demand into researching for biologically degradable drag-reducing agents.

New research suggests that mucilage, a viscous substance found in plants, exhibits drag-reducing properties. It fulfills the criteria of current demand; it has a natural and easily available source, and is biologically degradable. Now this area of research is expanding and exploring possible sources of mucilage that has drag-reducing properties.

This research aims to:

1) Identify and extract mucilage from plants that are native to Malaysia
2) Test the drag-reducing ability of the mucilage in aqueous liquids (like water).

Analysis of the experiments to be conducted will provide further insight on the potential of mucilage as a cheaper alternative to reduce drag by decreasing dependence on pumps.

1.2 Problem Statement

The purpose of this research is to produce natural mucilage from Malabar spinach and utilize it as a drag-reducing agent for aqueous liquids flowing in pipelines. The challenge is to produce not only an effective drag-reducing agent, but one that is environmental-friendly and can be financially attractive alternative to conventional solutions. This will help reduce the cost incurred for installation and maintenance of pumps to overcome the effect of drag in the flowing liquid.

1.3 Objectives

The objectives of this research are:

1. To extract mucilage from a natural and easily-available source.
2. To study the drag-reducing properties of mucilage in aqueous liquids.
3. To study the effect of pipe dimensions on effectiveness of mucilage.
4. To analyze the commercial application of the mucilage.

1.4 Scope of Study

The research will be bounded by the following parameters:

1. Mucilage will be extracted from Malabar spinach obtained locally.
2. The drag-reducing properties will be tested on water.
3. Pressure drop will be used to indicate the extent of drag reduction.
4. The manipulated variables in the experiments are pipe dimensions (length, diameter), concentration of mucilage and fluid flow rate.

1.5 Significance of Study

This research will benefit many industries since piping systems are an integral part of transporting fluids etc. This research will also provide a cheaper and more environmentally-friendly alternative to reducing pressure drop in piping systems. This research will study the commercial application of mucilage as a drag-reducing agent to be utilized in both industrial and domestic piping systems.

CHAPTER 2

LITERATURE REVIEW

2.1 Thesis Statement

Mucilage, a drag-reducing agent, can reduce the industry's dependence on pumping systems to overcome pressure drop in fluid flows, and an understanding of fluid flows, pressure drop, drag reduction, drag-reducing agents and mucilage will provide insight to the potential of mucilage in this specific area of interest.

2.2 Types of flow

Flow regimes are dependent on several factors such as the fluid's density and viscosity, surface roughness of the contacting solid (wall, pipe surface etc.), temperature and velocity. The Reynolds number is commonly used to describe the fluid flow profiles. Fluid engineers have to firstly estimate the Reynolds number range of the flow under study. Equation 2.1 below describes the dimensionless Reynolds number

$$\mathrm{Re} = \frac{\rho v L}{\mu} \qquad (2.1)$$

The following approximate ranges occur:

Table 2.1 Reynolds number range and corresponding fluid flow profile

Reynolds number range	**Fluid flow profile**
$0<Re<1$	Highly viscous laminar “creeping” motion
$1<Re<100$	Laminar, strong Reynolds number dependence
$100<Re<10^3$	Laminar, boundary layer theory useful
$10^3<Re<10^4$	Transition to turbulence
$10^4<Re<10^6$	Turbulent, moderate Reynolds number dependence
$10^6<Re<\infty$	Turbulent, slight Reynolds number dependence

Identifying the fluid flow profile helps to answer the basic piping problem: given the pipe geometry and its accessories (fittings, valves, bends, etc.), the desired flow rate and fluid properties, what pressure drop is needed to drive the flow? This problem also can be stated as: given the pressure drop available from a pump, what is the resulting flow rate? Problems like these are eminent in fluids engineering and crucial questions in designing piping systems (White, 2008).

2.3 Friction and pressure drop

Pressure drop is caused by fluid friction resistance. Equation 2.2 below describes friction factor *f*:

$$f = \frac{\Delta p D}{2\rho v^2 L} \qquad (2.2)$$

The relationship between flow rate in a pipe, Q and Δp is shown by equation 2.3 below:

$$Q = \frac{\pi \Delta p R^4}{8\mu L} \qquad (2.3)$$

When the fluid flow is laminar, the plot of Q against Δp is a straight curve from which viscosity can be determined. However when the fluid flow is turbulent, the plot will no longer be straight due to the change in “effective viscosity” of the fluid.

The friction factor depends on several parameters, such as flow rate, pipe size (diameter), length of pipe, pipe properties (surface roughness, material, etc.) and properties of pumped liquid. At turbulent mode, the friction factor is highly dependent on the inner surface of the pipe, especially pipe surface roughness.

In turbulent flow, swirling regions of fluids, called eddies are formed. These eddies rapidly transport mass, momentum and energy to other flow regions and create fluctuations. Even at a constant average flow rate, the eddy motions create significant changes in velocity, temperature and sometimes fluid density. Due to the complexity of eddy motions, experimental data and semi-empirical equations are used in calculations related to turbulent flow (Graebel, 2007). Figures such as the Moody chart (Figure 2.1) and equations like the Colebrook equation (equation 2.4) are immensely crucial in calculations related to turbulent flow.

$$\frac{1}{\sqrt{f}} = -2.0 \log \left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \qquad (2.4)$$

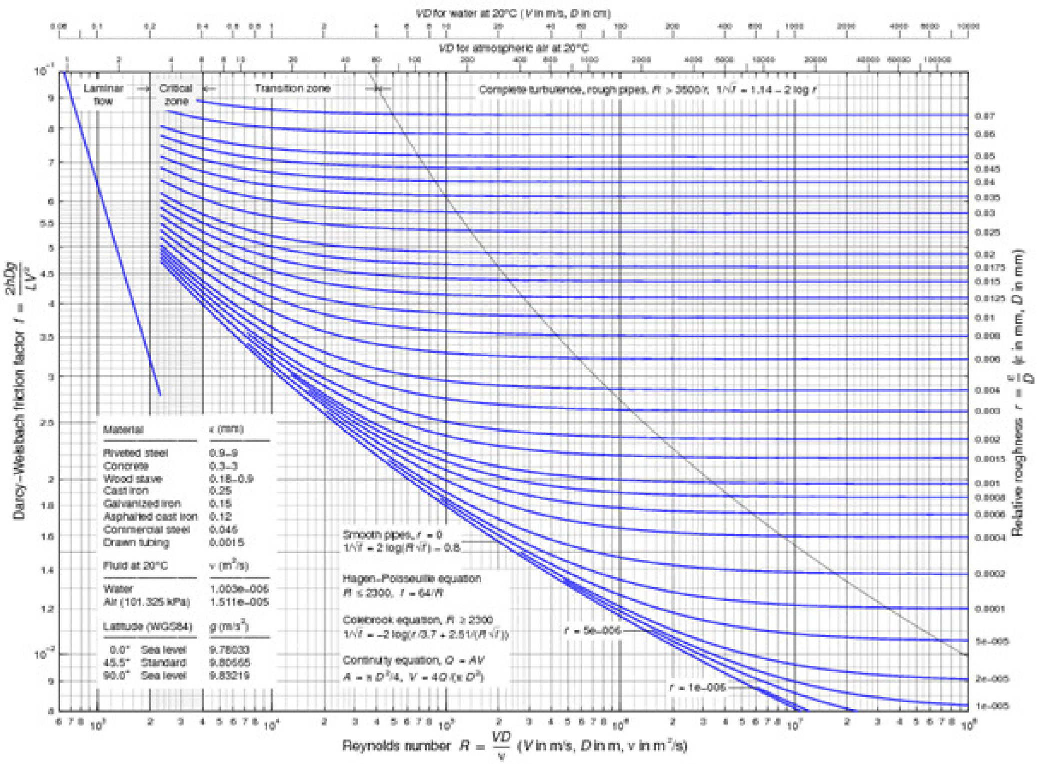

Figure 2.1 Moody Chart

In the analysis of piping systems, Δp is often expressed as head loss, h_L as shown in equation 2.5:

$$h_L = \frac{\Delta p}{\rho g} \qquad (2.5)$$

The pumping power required to overcome frictional resistance, $\dot{W}_{pump}$ can be calculated using equation 2.6 below:

$$\dot{W}_{pump} = Q\Delta p = Q\rho g h_L \qquad (2.6)$$

The equation above simply displays that when the pressure drop increases, the pumping power required increases. This (partly) explains the increased costs related to reducing pressure drop in piping systems.

2.4 Drag-reducing agents

Traditional drag-reducing agents are polymers, suspended solids and surfactants. Mucilage is a relatively new member to this group but shows great promise as a cheap and biodegradable drag-reducing agent.

2.4.1 Polymers

Polymeric chains have long been known to reduce drag effectively even in minute quantities. Drag reduction of up to 80% can be achieved by adding a few tens of ppm by weight of polymer (Singh, 2004). Drag-reducing polymer test fluids are the most commonly used agents today. Table 2.2 shows typical polymer test fluids used for drag reduction:

Table 2.2 Typical drag-reducing polymer test fluids

Water-soluble polymers	**Solvent-soluble polymers**
Poly(ethylene oxide)	Polyisobutylene
Polyacrylamide	Polystyrene
Guar gum	Poly(methyl methacrylate)
Xanthan gum	Polydimethylsiloxane
Carboxymethyl cellulose	Poly(*cis*-isoprene)
Hydroxyethyl cellulose	

Drag reduction using polymer has been studied by many researchers like Truong (2001), Absi *et. al* (2009), Browstow *et. al* (1999), and Fossa & Tagliafico (1995). In general, the effectiveness of a polymer as a drag-reducing agent increases when the molecular weight increases. A longer polymer chain increases probability of entanglement and interaction with flow (Truong, 2001). The configuration of the polymer molecule is also important in determining drag-reducing properties:

1. Polymers that are linear show drag-reducing properties.

2. Highly-branched polymers like gum arabic and dextran do not show drag-reducing properties.
3. Polymers with increased coil extensions will produce higher drag reduction.
4. Polymers with higher molecular weights are more susceptible to mechanical degradation.

A common theory of polymer drag reduction is that highly elastic polymer chains restrict the motion of large eddies and the transport of momentum from the large eddies to dissipating small eddies, hence reducing drag.

Truong (2001) also found that at constant polymer concentration and pipe diameter, the degradation rate is proportional to wall shear stress. Reducing susceptibility to mechanical degradation can be done in two ways:

1. Grafting polysaccharides with flexible polyacrylamide branches
2. Cross-linking of polysaccharides at concentrations below those required for gel formation.

Studies conducted by Absi *et. al* (2009) on dilute polymer solutions showed that the polymer chains resemble rigid long fibers which align in the flow direction. The flow is dominated by the anisotropy produced by this behavior, shedding light on how a few ppm of polymers can effectively reduce drag in turbulent flows.

Browstow *et. al* (1999) described a DR model in dilute polymer solutions on two levels:

1. Salvation of macromolecular chains
2. Formation of relatively stable domains

The model suggested that at turbulent mode, polymer chain sequences will align with the flow (good sequence). However due to the structure of the chains, some sequences will be perpendicular to the flow direction (bad sequence). The combination of both good and bad sequences creates a domain as shown in Figure 2.2 below:

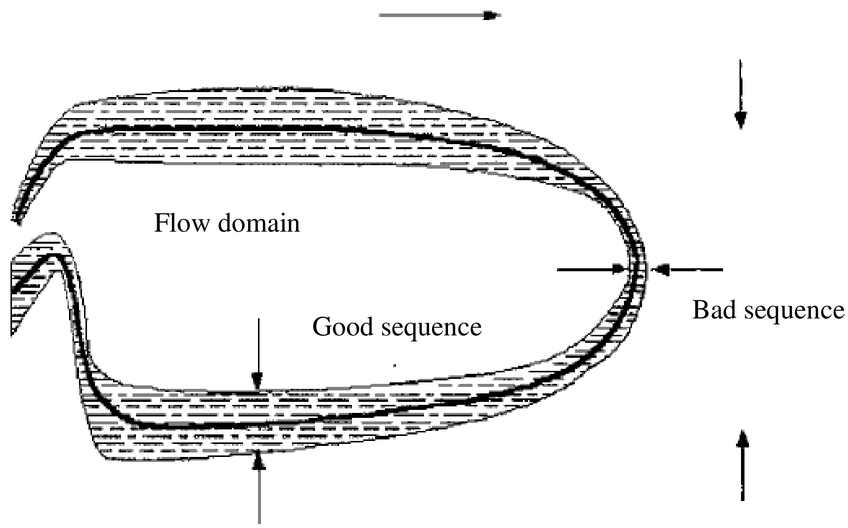

Figure 2.2 Solvation and domain structure in flow of dilute polymer solutions

Brownian dynamics simulations conducted in the research described that in turbulent mode, an increase in shear rate reduced the rate of entanglement of polymer chains and the number of interchain contacts, encouraging the formation of more domains and increasing DR.

The research also emphasized on the definition of turbulence as "eddies within eddies within eddies". Eddies are typically smaller than the domains and the latter act as energy sinks, where energy dissipation solvates polymer chains in localized sequences. The solvated polymer chains will be substituted by another polymer chain, hence the energy dissipation process will be continuous one.

Fossa & Tagliafico (1995) took a more practical approach to study the application of DR polymers in water for heat exchangers of spacecraft. The study determined that the polymer additives used can suppress turbulence. The study also suggested that polymer additives be used for emergency purposes, open-loop and/or discontinuous operations due to the polymers' tendency to age and degrade in closed-loop systems. The following conclusions are noted:

1. Drag reduction increases when Reynolds number (hence turbulence) increases.
2. The Fanning friction factor of water with added polymer decreases compared to that of pure water only in turbulent mode. Entry length is a factor in this behavior.
3. The Fanning friction factor increases with increasing polymer concentration at laminar flows.

2.4.2 Suspended solids

The drag-reducing properties of suspended solids are not as extensively researched as polymers but they are favored because they can be added (and removed) to (and from) the liquid easily, and they are mechanically stable. There are two main types of suspended solids used:

1. Granular/spherical particles
2. Fibers

Table 2.3 shows examples of suspended solids used for drag reduction.

Table 2.3 Suspended solids used for drag reduction

Suspension	**Flowing Fluid**
Sand	Water
Coal, fly ash, clay, activated charcoal	
Wood and wood pulp	
Fibrous wood pulp	Test fluid of guar gum
Emery	Water
Thoria	

Nylon fibers	Water
	Polymer test fluid
	Polymer test fluid + aerosol OT
Rayon fibers	Water
Asbestos fibers	Water
	Polymer test fluid
	Aerosol OT test fluid
Yellow dye crystals	Their mother liquid

The presence of suspended solids allows dissipation of turbulent energy and transfers momentum from bulk liquid to the wall, increasing hydraulic resistance of the flow. The mechanism is two-fold:

1. The solids reduce the intensity of the pulsations from the carrier phase (liquid).
2. A transfer of momentum from the liquid to the solids causes these solids to be dispersed across the fluid, increasing the drag reduction.

When concentration of suspended solids increases, the drag reduction also increases (Derevich *et. al*, 1985). This behavior is explained by the migration of the solids across the flow regime. The movement of solids creates two effects:

1. Additional transfer of turbulent energy from the core of the flow to the viscous sublayer, reducing the dampening of the carrier phase's pulsating motion.
2. Additional momentum transfer of averaged motion towards the wall, increasing hydraulic resistance of the flow.

These two effects produce an increase in drag reduction when the concentration of suspended solids increases.

Inaba *et. al* (2000) studied pulp fiber as a DRA in water flowing through a circular pipe. The main constituent of the fiber is cellulose, which is a kind of polysaccharide which does not dissolve readily in water. Hence the liquid containing the fibers form a suspension. The study found that the viscosity of the suspension was greater than that of water. Each pulp fiber/pulp fiber lump had a local velocity, which increased when the fluid velocity increases.

Povkh & Stupin (1972) performed experiments on nonhydrolyzed 8% polyacrylamide as the macromolecular additive. The solid phase consisted of quartz sand, ash, clay, brown coal, and hard coal. The optimum concentration of polyacrylamide is 2.4 x 10^{-4} g/cm^3, when a maximum DR of 58% is achieved. However when sand is added to the solution, the DR is less than when solid concentration is zero. The maximum DR is again achieved at the polyacrylamide concentration of 2.4 x 10^{-4} g/cm^3. Increased sand concentration decreased the DR. Similarly, when ash is added, DR increases to a maximum point when polyacrylamide concentration is 5 x 10^{-4} g/cm^3. No DR occurred when brown and hard coal, and clay were added. The study showed that addition of polyacrylamide can enhance the DR properties of suspended solids like ash and sand.

2.4.3 Surfactants

Surfactants reduce surface tension of a liquid and are usually organic compounds. Derived from combining "surface acting agents", surfactants have two parts:

(i) Hydrophilic head which has an affinity for water (polar) molecules.
(ii) Hydrophobic tail which has an affinity for oil (non-polar) molecules.

Figure 2.3 shows a typical surfactant molecule structure:

Figure 2.3 Structure of surfactant molecule

The molecules rest at the interface between two liquids or between a liquid and a solid. At a critical concentration value, the molecules begin to aggregate, forming micelles. The shapes of these micelles depend on factors such as concentration, solvent type and molecular structure; they can be spheres, rods or discs. Micelles are always in thermodynamic equilibrium with the surfactant molecules, hence the association (and dissociation) of surfactant molecules is a reversible reaction. When the concentration micelles reach a critical value, worm-like structures are formed (Truong, 2001). The processes are described in the following Figures 2.4 and 2.5:

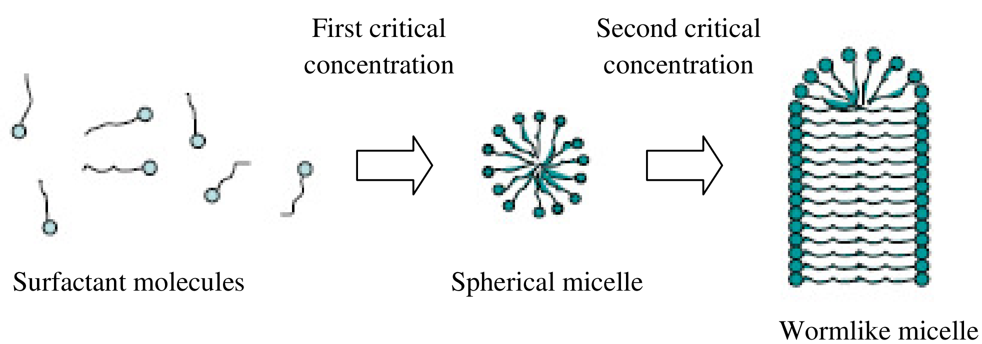

Figure 2.4 Progressive formations of surfactant micelles

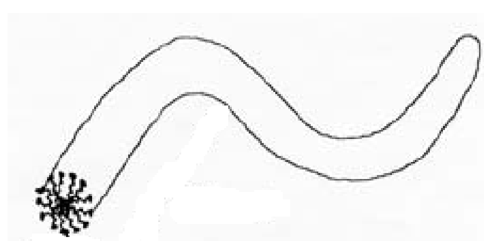

Figure 2.5 Worm-like micelle structure

Surfactants are classed according to the electrical charge of the head group:

1. Anionic

    Alkali metals and ammonium soaps can achieve 30%DR for 0.2% sodium oleate test fluids. Addition of an electrolyte such as KCl can increase drag reduction. Anionic surfactants are often precipitated out of test fluid after interacting with ions like calcium that are commonly present in tap and sea water, hence reducing their durability.

2. Cationic

    The most studied cationic surfactant is cetryltrimethylammonium bromide (CTAB). An advantage of using cationic surfactants is these complex soaps do not precipitate out of test fluid as how anionic surfactant does. However cationic surfactants are costly and thermally unstable, hence limiting their applicability. They are also not very biodegradable (Chapman, 2005).

3. Zwitterionic

    Zwitterionics have both positive and negative charges on the surfactant molecule, resulting in zero net charge. Zwitterionic surfactants are advantageous in that they are tolerant to hard water, strong electrolytes, oxidizing and reducing agents, low toxicity and compatible with other surfactants (Chapman, 2005).

4. Non-ionic

    Non-ionic surfactants are more effective than both anionic and cationic surfactants because they do not precipitate out of test fluid and they are thermally stable, hence they can be used in a variety of test fluids. Temperature is an important factor in increasing/decreasing the drag-reducing abilities of non-ionic surfactants. However, more research is required to fully comprehend the drag-reducing properties of non-ionic surfactants.