INVESTIGATING DRAG REDUCTION USING TURBULENCE ALTERING PSEUDO-SURFACES (TAPS)

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ABSTRACT

The issue of drag reduction in pipes has already been widely researched and studied. Currently the most popular method for reducing drag in pipes employed commercially is through the use of additives. However, these additives do have drawbacks such as mechanical degradation, altering the chemical and physical properties of the fluid they inhabit as well as being toxic and non-biodegradable for the most part. This has spurred new research aimed to exploring more nature friendly, non-additive means of drag reduction. Among these techniques the most popular ones include riblets, dimples, oscillating walls, compliant surfaces and microbubles but each of these techniques have their respective drawbacks especially when considered for drag reduction in pipes. The present study introduces a novel non-additive technique that employs narrow strips of flexible elastic material in an arrangement mimicking the tentacles of a squid. This form of biomimickry has been frequent among the non-additive methods mentioned previously. The device which has been named the Turbulence Altering Pseudo-Surface (TAPS) consisted of 12 strips of elastic material (neoprene and silicone were tested in this study) of varying lengths of 0.2m, 0.3m, 0.4m, 0.5m, 0.6m and 0.7m with 0.005m width and 0.003m thickness each. The %DR was measured across 4 different testing section lengths, 0.5m, 1.0m, 1.5m and 2.0m spans. The flowrates tested were 6.0m^3/h, 6.5m^3/h, 7.0m^3/h, 7.5m^3/h, 8.0m^3/h, 8.5m^3/h, 9.0m^3/h and 9.5m^3/h. The results of the series of experiments carried out were both stimulating and intriguing. On one hand, the maximum %DR achieved is 65% with TAPS made of 0.6m strips of neoprene, but this is followed by an immediately negative pressure gradient change across the consecutive testing sections. On the other hand for TAPS made of 0.7m silicone strips, there is a peak recorded at 42.7% DR with considerable persistence of effect further downstream across the proceeding testing sections. These results raise a perplexing question of whether a localized high %DR is preferred or if a smaller but persisitent effect is better for flow improvement purposes. Whichever the case, this research has profound and important implications for the future of drag reduction in pipes as it has dispelled one of the age old myths, that reducing the effective pipe diameter always results in an increase in drag. There is immense potential in this field of research and plenty of room for improvement in future works.

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LIST OF SYMBOLS

C	Concentration
cm	centimeter
D	Diameter
f	Darcy friction factor
g	Acceleration due to gravity
h	height
ID	Internal diameter
L	Length
Kg	Kilogram
kW	kilowatt
L	Litre
L	Pipe length
m	meter
mbar	milibar
mL	mililiter
mm	Millimeter
N	Newton
P	Pressure
Pa	Pascal
ppm	Parts per million
s	Second
t	thickness
T	Period

V	Average velocity
w	width
$\%DR$	Percentage drag reduction
$°C$	Degrees celcius
ρ	Fluid density
μ	Dynamic viscosity of fluid
μm	micrometer
ΔP	Change in pressure
D_m	Maximum displacement
m^3/h	Cubic metres per hour
W_m	Maximum spanwise wall velocity

LIST OF ABBREVIATIONS

3D	Three dimensional
CPU	Central processing unit
CTAC	CetylTrimethyl Ammonium Chloride
DNS	Direct numerical simulation
DR	Drag reduction
DRA	Drag reducing agent
ID	Internal diameter
LSS	Large scale structures
NaSal	Sodium Salicylate
NWS	Near wall structures
PT	Pressure transmitter
Re	Reynolds number
SCADA	Supervisory control and data acquisition
TAPS	Turbulence altering pseudo-surface

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Drag reduction is a field that has always been under scientific scrutiny for its obvious economic and energy saving benefits. It is essentially the science of flow improvement through the reduction of frictional pressure drop across a pipe or channel. Oil pipeline conduits, oil well operations, flood water disposal, fire fighting, field irrigation, transport of suspensions and slurries, sewer systems, water heating and cooling systems, airplane tank filling and marine systems are all industries in which this science can be applied. This highly abbreviated list is but the tip of the iceberg which represents industries that could benefit from the science of drag reduction. Any operation which involves some form of fluid transport or another has a vested interest in drag reduction to reduce cost and increase efficiency. The potential to save energy through drag reduction is the crux of all research in fluid flow and underlines the sheer magnitude of possibilities that this science brings with it.

Currently, the primary method used for achieving drag reduction is through the addition of drag reducing agents (DRAs) which are usually high molecular mass polymers, surfactants or suspended solids and have been known to reduce drag up to 80% (Shah, Kamel and Zhou, 2006). These additives are generally preferred for their simplicity and effectiveness. Simply adding a few parts per million of the additive is enough to reduce drag significantly – resulting in 20-80% drag reduction (Gyr and Bewersdorff, 1995; Hoyt, 1972; Landahl, 1973; Liaw, Zakin and Patterson, 1971; J. Lumley, 1969; J.L. Lumley, 1973; McComb, 1991; Nieuwstadt and Den Toonder, 2001;

Virk, 1975; White and Mungal, 2008). These additives are also easy to use, store, transport and most importantly are a cheap and economical method of reducing drag.

That being said though, there are also several drawbacks from using polymers. Certain niche industries are unable to use these miraculous solutions to the drag problem. There is also the ongoing issue of environmental effect deriving from these additives as they are for the most part toxic in nature. There is therefore a growing interest in non-additive means of drag reduction. While this interest is mainly academic at the moment (there has been limited evidence of commercial use of these non-additive methods of drag reduction), the research is nonetheless an exciting and novel field with great prospects and huge possible application in the future.

Researchers have begun to turn to new methods of drag reduction that do not involve additives. These new, non-additive methods include among others – riblets, dimples, humplets, oscillating walls, compliant surfaces, water-resistant coating and microbubbles. While these are the most popular other methods such as the use of water repellent surfaces (Watanabe and Udagawa, 2001) and thin lubricating films using air (Fukuda et al., 2000) also exist but have not been explored as thoroughly as the first five. The main purpose of all this research is to create a cheap (possibly even free) method of drag reduction so as to reduce or eliminate the need for additives.

1.2 PROBLEM STATEMENT

The essential problem most research on fluid flow tends to address is drag reduction. As far as blanket, one solution fits all problem solvers go, additives remain the simplest to use and the most economically competitive. It is hard if not impossible (at the moment at least) to displace additives as the solution of choice for most commercial drag reduction needs. However, this particular solution does come with its own set of problems.

Despite their apparent advantages, additives necessarily alter the physical and chemical properties of the fluid they are added into, thus making them unsuitable for a wide range of applications such as in the pharmaceutical, specialty chemical and food & beverage industries. In these industries, fluid parameters such as specific heat capacity, density and viscosity are of utmost importance and the changes introduced by additives cannot be tolerated. Also the addition of substances to a fluid decreases the purity of the fluid which is undesirable in a lot of industries. The most effective polymers are also often toxic and hazardous to the environment, further compounding their infeasibility. To make additives suitable for these industries, many additional stages must be introduced which would then increase costs and nullify the savings due to the additive.

In addition to this, it should be noted that DRAs, particularly polymeric DRAs degrade and lose their effectiveness with time. In the act of absorbing the turbulent energy and dissipating it into elastic energy, the long chained polymers undergo scission due to high shear stresses and thus mechanically degrade. In fact, it was this exact mechanical degradation of polymers that Toms was researching when he accidentally discovered the effect of polymer additives on flow. This degradation continues until the polymers are shred to a length that is too short to be influenced by turbulent shearing. At this length, the truncated polymers become significantly poorer drag reducing agents and fresh polymers must be added to achieve acceptable DR. The injection of fresh DRAs is a recurring cost which although still results in net savings, somewhat reduces the attractiveness of DRAs as a solution to turbulent flow in pipes.

All these problems beg the question of why an alternative is not available. This research aims to address this question. The problems listed above point out that non-additive methods of drag reduction have a rather large subset of industries in need of flow improvement to capitalize on.

1.3 OBJECTIVES OF RESEARCH

The objectives of this research are:

1. To investigate a novel mechanical technique of drag reduction using flexible bands of elastic material.

2. To evaluate the efficiency of this technique in pipes carrying water.

1.4 SCOPE OF RESEARCH

The scopes of this research are discussed below:

i. A device using flexible elastic bands is designed to absorb turbulent energy. The device is made using two different materials: neoprene and silicone.

ii. The neoprene device is made of bands with a width of 5mm, thickness of 3mm and varying lengths of 20cm, 30cm, 40cm, 50cm, 60cm and 70cm.

iii. The silicone bands were made from two different widths, the first being 5mm and the second being 3mm. For each of these widths, and a thickness of 3mm, the lengths of 20cm, 30cm, 40cm, 50cm, 60cm and 70cm were used to make the device.

iv. The effect of each individual version of the device on pressure drop is measured across different testing section lengths. The pressure drop over the first length of 0.5m between the first pressure transmitter, PT-101 and the second pressure transmitter, PT-102 is denoted as PT-112. Similarly, the pressure drop across the 1.0m length between PT-101, the first pressure transmitter and PT-103, the third pressure transmitter is denoted as PT-113. PT-114 and PT-115 are the pressure drops across the 1.5m and 2m lengths respectively. These are measured from the difference between PT-101 and PT-104 to give PT-114 whereas the difference between PT-101 and the final pressure transmitter PT-105 gives PT-115.

v. Experiments are carried out in a closed loop liquid circulation system with pipes of 1.5 inch internal diameter.

vi. Flowrates of 7.0, 7.5, 8.0, 8.5, 9.0 and 9.5 cubic meters per hour were tested. These flowrates correspond to Reynold’s numbers of 75288, 80666, 86044, 91421, 96799 and 102177 respectively for the flow conditions used in these experiments.

vii. Water was used as the fluid medium of choice.

1.5 SIGNIFICANCE OF STUDY

To begin with, the present study aims to disprove a fundamental intuitive logic – that reducing the average or effective diameter of a pipe will always necessarily reduce the flow thoughput. In coorecting this misconception, a new avenue of research in fluid flow improvement is born. This research presents a novel mechanical, non-additive means of drag reduction that involves low initial cost and little to no maintenance or upkeep fees while producing a reasonable amount of energy savings. This method is also nature friendly compared to additives and does not affect the fluid's physical or chemical properties. It is a long term solution to pumping power loss problems and this study represents a foot in the doorway to new and exciting areas of research in drag reduction mechanics. The device designed is aimed at industries involving fluid flow which cannot make use of additives due to process restrictions; thus there is real commercial potential for the device that results from this research. If nothing else, the present body of work provides a sound foundation for future research targeted at similar non-additive means of drag reduction.

1.6 OVERVIEW OF THE THESIS

This thesis contains five chapters beginning with Chapter 1, the introduction. In this chapter, the background of drag and its association with pumping power losses are explained. Chapter 1 also outlines what this research aims to achieve and the boundaries of the experiments conducted.

In Chaper 2, a review of related literature is presented which discusses the fundamental theories related to drag in depth as well as the past methods used to reduce it. These methods are separated into the non-additive and the additive methods, each category having multiple techniques which are explained individually.

In Chapter 3, the methodology, apparatus and details of how the experiment was carried out are outlined. The precise measurements of the TAPS, the details of the equipment used, the experimental set up and the procedural steps are elaborated on in great detail.

Chapter 4 presents the results of the experiments and give an analysis of the data collected, explaning prominent trends and providing possible reasons for the observed outcomes. The effects of each variable tested in the experiment were explored one by one starting with the most prominent findings. The explanations for the results obtained and possible mechanisms for the drag reduction phenomena observed were also given.

Finally in Chapter 5, the conclusion and recommendations for future research are presented. References and appendices are also provided to support the claims made in this study as well as to aid understanding.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses a review of previous literature related to the field of drag reduction with specific attention paid to non-additive means of achieving it. The chapter begins with a brief introduction on drag and the common theories associated with turbulence and fluid flow. It then proceeds to explore the more common methods of flow improvement which are polymers, surfactants and suspended solids. Finally the chapter presents a comprehensive review of successful non-additive methods of drag reduction that have been popular recently and in the past.

2.1 FUNDAMENTALS OF FLUID FLOW

2.1.1 Turbulence and Drag

Turbulence refers to the degree of chaos present in a fluid state. A simple and standardized way to represent this is using the dimensionless Reynolds number (Re) which is given by Eq. (2.1) first conceived by Reynolds (1883).

$$\mathrm{Re} = \frac{\rho V D}{\mu} \tag{2.1}$$

Where: ρ is the fluid density (kg/m^3), V is the fluid velocity (m/s), D is the hydraulic diameter or internal diameter of pipe (m) and μ is the dynamic viscosity of the fluid (Pa.s or N.s/m^2 or kg/(m.s)). The numeric value of the Reynolds number can be used to determine the state of the fluid flow for which the calculations were made. These states are divided into laminar, transitional and turbulent flow. Laminar flow occurs at Reynolds numbers less than 2000 and are characterized by smooth, constant fluid motion; generally uninterrupted by swirls and vortices and pressure losses in this type of flow is comparatively small. Transitional flow occurs at Reynolds number exceeding 2000 but less than 4000. In this transitional region, the flow is less quiescent and there are some notable pressure losses. At Reynolds numbers exceeding 4000, the flow is considered to be turbulent. Turbulent flows are chaotic and unstable with violently fluctuating velocities and pressures. Energy must be continuously supplied to the flow in order to maintain a given flowrate because energy is frequently dissipated into the wall in the form of heat and sound. It is this form of flow that the remainder of this study will focus on and it is also this form of flow that is most commonly encountered in industrial applications.

Drag reduction can be calculated from a turbulent flow given two pressure drop measurements across a specific region of the pipe under two different conditions. Equation (2.2) can be used for this calculation.

$$\%\mathrm{DR} = \frac{(\Delta Pb - \Delta Pa)}{\Delta Pb} \text{ x } 100\% \tag{2.2}$$

Where ΔP_b is the pressure drop before any modifications or the control run pressure drop and ΔP_a is the pressure drop after using some drag reduction technique and %DR is the percentage drag reduction achieved.

2.1.2 Near Wall Structures

The near wall region of the wall bounded flow although represents a very small portion of the entire flow is a crucial region due to the formation of near wall structures in this region which dramatically influence the fluid flow. The region directly adjacent to the wall is known as the viscous sublayer. The flow in this region is essentially laminar since the absolute velocity at the wall is zero for a non-slip boundary condition. Above the viscous sublayer is the buffer layer in which the flow is transitional. It is in this region that near wall structures form and migrate to the main bulk fluid flow which is also known as the log law region, since the velocity profile increases exponentially at this point up to the maximum bulk fluid flowrate at the midpoint of the pipe. These separate regions are illustrated in Figure 2.1.

The primary focus of any research in the field of fluid flow is to reduce drag and improve flow. To achieve these objectives, a sound understanding of the complex mechanics of fluid flow must first be acquired. It has in recent times become common knowledge that streamwise vortices in the near wall region are the main causes for a majority of sweep and ejection events and by extension the turbulent stresses and excess skin friction that is often associated with these events (Jeong et al., 1997; Robinson, 1991). These near wall vertical structures are believed to be closely tied to high-skin friction and large shear stress created by the inrush of high-speed fluid stimulated by the said vortices (Choi et al, 1993; Kravchenko et al., 1993; Solbakken and Anderson, 2004). Therefore it is of paramount importance that these streamwise vortices be suppressed in the buffer layer or their effect on the wall regulated in such a manner as to reduce drag.

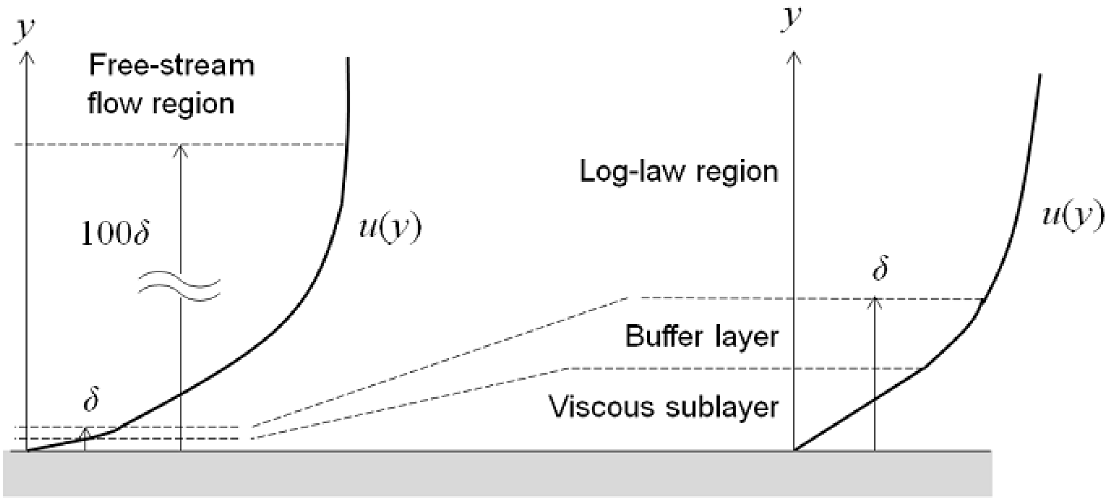

Figure 2.1:Velocity profile and flow regimes for wall bounded flow. (Frei, 2013)

Near wall vortical structures are not stationary but are dynamic and tend to interact with each other in a complex ongoing process that is statistically repeatable. This process is popularly known as the bursting phenomenon or burst sweep cycle and is dominated by the presence of streamwise vortices, low-speed streaks, the inflectional profiles and the resulting instabilities. Although the birth-maturation-death cycle and manifestations of near wall structures are not clearly understood, low speed streaks are almost always identifiable and may be the single most important structural feature in the near-wall region (Pollard, 1998). Alternately, Kim (1992) is of the opinion that it is near-wall streamwise vortices that should be viewed as the most important turbulent structure from the perspective of drag manipulation. To reconcile these two opinions, a closer examination of these two structures and their interactions are warranted.

The near-wall streamwise vortices are vortices with axes aligned with the main flow direction and they appear in isolation from others (this appears to be the norm) and occasionally in pairs whereas low speed streaks on the other hand are part of the burst cycle associated with coherent structures (Pollard, 1998). When a pair of vortices is in close proximity with each other, a bursting event occurs where the fluid between these two vortices is ejected upwards and away from the wall producing an inflection in the velocity profile. This ejection is acountered by an inrush of high momentum outer region fluid which splashes against the wall generating large Reynold's stresses (hence the name burst-sweep or ejection-sweep cycle). The low speed streak therefore most likely refers to the updraft side of the vortex flow and these structures are fundamentally connected and possibly unable to exist without the presence of the other.

The Reynolds stress variations have been reported to swing by as much as 50% of the local mean flow (Kasagi et al., 1995) and the correlation between the Reynolds stress and turbulent structures have also been researched to some extent (Kasagi and Shikazono, 1995; Sumitani and Kasagi, 1995). Figure 2.1 shows a simplified flowchart synthesized by Blackweleder (1998) representing the possible sequence of events that lead to bursting cycles and the role large scale structures (LSS) and streamwise vortices play in causing these cycles.