Optimization of Mesh Separator Systems for Interlayer Flow in Wound Gel Rolls

A thesis submitted by

Sarah E. Briggs

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Advisors: Luisa Chiesa
Richard Wlezien

ABSTRACT

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By Sarah Briggs

Mesh separators are typically used to maintain uniform fluid flow between gel roll layers during aging in the gel fabrication process. In order to reduce production cost and conserve energy, the manufacturing process must be optimized to reduce aging time. In this work we address the optimization of the mesh separators with respect to liquid flow rate. Several mesh separator designs were tested under aging conditions to determine the best separator configuration for maintaining uniform flow between gel layers to decrease aging time. Tests of single-layer separators resulted in very high pressure drops at low flow rates, indicating the flow channel was blocked by gel. A layered separator design performed best, producing significantly lower pressure drops for the same flow rates. Optimization of the separator system revealed two options as viable solutions: a foil layered system and a three layer net mesh system.

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NOMENCLATURE

Bi	Biot Number
h	Heat Transfer Coefficient
k_{gel}	Thermal Conductivity of Gel
L_{gel}	Thickness of Gel
$\dot{Q}$	Heat Transfer Rate
A_s	Surface Area
T_s	Surface Temperature
T_∞	Ambient Temperature
$\dot{m}$	Mass Flow Rate
c_p	Specific Heat
T_e	Temperature at Exit
T_i	Temperature at Inlet
Sh	Sherwood Number
Re	Reynolds Number
Sc	Schmidt Number
D_H, d_h	Hydraulic Diameter
Q	Volume Flow Rate
P_{loss}	Pressure Loss
Nu	Nusselt Number

$L_{channel}$	Height of Channel
k_{fluid}	Thermal Conductivity of Fluid
$\vec{u}$	Velocity Vector
ρ	Density
g	Gravity
μ	Dynamic Viscosity
U	Average Fluid Velocity

Chapter I

INTRODUCTION

Kistler [1] created the first aerogel in 1931 by supercritically drying a wet sol-gel, also known as an alcogel. Aerogels are extremely porous solids with very low thermal conductivities and are very effective thermal insulators. Aerogel insulation blankets, composite blankets of aerogel and fiberglass matting, are an innovative advancement in the insulation industry. They provide excellent insulation properties and can be used in many applications. If utilized strategically, aerogel blankets can conserve significant amounts of energy when used for insulation applications.

Energy consumption rates continue to grow throughout the world and conserving energy has become an important societal issue. Finding cost effective, energy conserving manufacturing processes is extremely important. This research produces two viable solutions to help optimize manufacturing processes during aging of aerogel blankets and may provide an exciting yet simple solution for reducing cost and conserving energy. Additionally, this work is the first to study the application of mesh separators in the manufacturing of insulation products, and more generally, mesh separators to enhance flow between alcogel roll layers.

The manufacturing process of alcogel blankets consists of four steps including casting, chemical aging, supercritical extraction, and heat treatment. During casting a mesh spacer, which will be referred to as the net mesh, is rolled with an alcogel blanket to keep the roll layers separate. The separator also creates a flow channel between the gel layers through which heated aging fluid may flow. This thesis addresses the optimization of fluid flow between alcogel layers during chemical aging.

Research completed by Orellano [2] showed that increasing inner roll temperature during aging by flowing heated aging fluid through roll layers increases the rate of chemical aging processes and helps decrease aging time. However, inconsistencies in aerogel blanket quality and temperature distribution throughout the roll during aging suggest the current separator used in industry is inadequate and the aging fluid does not flow uniformly between the roll layers. In fact, it is believed that portions of the roll remain entirely unexposed to the aging fluid. The purpose of this research is to design and test mesh separators and separator systems capable of separating alcogel layers in a roll, while allowing the aging fluid to flow uniformly through the roll layers. It is important that the optimized separator system minimally decreases aerogel blanket production and space constraints are thoroughly considered when designing the ideal separator system.

The roll/separator geometry creates unique flow conditions, which must be understood to determine the best separator system for manufacturing aerogel insulation blankets. Particularly, the heat transfer characteristics of the heated aging fluid flowing through the alcogel roll layers are important and should be considered when choosing the best mesh separator. The Biot number, defined in equation 1.1, is a parameter that measures the ratio of a systems resistance to heat conduction to its resistance to heat convection and gives valuable insight into the heat transfer characteristics of certain flow processes [3].

$$Bi = \frac{hL_{gel}}{k_{gel}} \tag{1.1}$$

Prapas [4] showed that our system, which consists of alcogel layers on either side of a mesh separator, results in a high Biot number system on the order of 38. A high Biot number indicates the conduction thermal resistance is high in our system. This means that the heat transfer between the alcogel and the flowing aging fluid is conduction dominated. It follows that the inner roll temperatures are best increased by increasing and maintaining uniform flow of heated aging fluid between the alcogel layers.

Similar flow processes to those incurred in alcogel rolls have been studied in the past, but have fundamental differences when comparing heat transfer characteristics. Thus far, mesh separators have been studied extensively for ultrafiltration applications in which the mesh separators were used to enhance mass transfer through membranes. These ultrafiltration systems have similar flow processes to those studied in this work. However, the heat transfer characteristics of ultrafiltration processes result in low Biot number systems [4]. This work is the first to investigate mesh separators for high Biot number systems.

The ideal separator for our system would maintain uniform flow between alcogel layers for low induced flow rates without producing high pressure drops across the flow channel. A mesh separator that meets these requirements would allow one to obtain uniform interlayer temperatures without inducing high pressure drops across the alcogel roll. Obtaining uniform interlayer temperatures would decrease aging time. Yet, how do we determine the best mesh separator design for this application?

Pressure drop measurements of fluid flowing through a mesh separator lying between two alcogel layers provides insight into flow conditions within the flow channel. High pressure drops for relatively low flow rates indicate the flow is heavily obstructed, whereas low pressure drops indicate low obstruction levels. Uniform flow would not be maintained if flow is obstructed between the alcogel layers. Pressure drop tests were conducted for fluid flowing through mesh separators with alcogel layers on either side to determine the best mesh separator for maintaining flow between alcogel layers. Two separator systems emerged as feasible solutions: a foil layered system and a three layer net mesh system.

Chapter II

OBJECTIVE

We look to optimize a manufacturing process used in industry, which entails the flow of an aging fluid between alcogel layers separated by a mesh spacer. The goal of this research is to optimize aging time by optimizing the flow of hot aging fluid between alcogel roll layers. This work will determine the best separator system to enhance the flow of aging fluid between alcogel layers by redesigning and testing several mesh separator systems.

As previously stated, the flow conditions in manufacturing gel roll result in a high Biot number system. The high Biot number of our system indicates the heat transfer process is “conduction dominated” and resistances to convective heat transfer are relatively low. Since syneresis and gelation reaction rates increase with temperature [5], the aging process will accelerate with higher convective heat transfer between the heated aging fluid and the gel. In order to increase the rate of convective heat transfer from the alcohol to the alcogel, one must increase and maintain uniform flow between the layers. This may be achieved by increasing the pressure drop across the flow channel, increasing the cross sectional flow area by increasing the channel height, and/or increasing the overall surface area of alcogel exposed to heated aging fluid. We will optimize a mesh separator to increase both flow rate between alcogel layers and the overall surface area of alcogel exposed to heated aging fluid without requiring increased pressure drops across the flow channel.

Design constraints imposed by manufacturing conditions must be considered when choosing the best mesh separator system since we must simultaneously optimize aging and manufacturing processes. An ideal mesh separator must be durable, flexible, and maintain uniform flow between alcogel layers without significantly increasing the overall height of the mesh separator. In fact, the mesh separator will be rolled within the alcogel layers and recycled multiple times, which requires it to be flexible and durable. Increasing the channel height significantly would decrease the amount of alcogel that can fit into an aging vessel, and thus less aerogel product would be manufactured. In this work several separator systems are designed and tested in order to develop the optimum mesh separator to enhance the flow of aging fluid between alcogel layers, while limiting loss of final product.

Chapter III

BACKGROUND

3.1 Aerogels

Aerogels have extremely low thermal conductivities ranging from 0.016 to 0.20 W/m·K [4], which provide excellent insulation properties. An aerogel's conductivity is comparable to that of air and other insulation products, which have thermal conductivities of 0.026 W/m·K and 0.026 to 0.091 W/m·K respectively [6]. Aerogels also have very low densities ranging from 0.03 to 3.5 kg/m_3, which are the lowest of any solids [4]. Any processes involving the storage, production, and/or management of heat may benefit from aerogel insulation products. As a result, aerogels have become of great interest in many energy industries. One revolutionary aerogel product in the insulation industry is a composite blanket made of aerogel and fiberglass matting. Before discussing composite insulation blankets in great detail, it is important to fully understand the science behind aerogels.

The production of an aerogel involves several manufacturing steps. The two most time consuming processes are aging and supercritical drying. The aging process begins after gelation, but before supercritical drying. The alcogel (pre-dried aerogel) structure is formed through a series of condensation reactions between SiOH molecules. After gelation, the composition, structure, and properties of the gel continue to change with time in a process called aging. The subsequent drying of the gel is strongly influenced by the structure developed during aging and the intricate physical and chemical changes that take place during aging and super critical drying have been studied in depth [5]. These two processes are the most energy consuming. Optimizing these processes is crucial to reducing the overall cost of aerogel insulation products, which are the most expensive of all available insulation materials.

3.1.1 Aging

Four chemical and physical changes occur during the aerogel aging process. They include polymerization, syneresis, coarsening, and segregation. Polymerization will occur with or without evaporation of the alcohol from the gel and accounts for the initial chemical and physical changes which occur immediately after gelation. Condensation reactions between silanol (SiOH) groups continue to occur throughout Polymerization. Hydrolysis reactions may continue as well. Polymerization results in a change of composition and flexibility of the gel. Hydroxyl levels decrease throughout the gel and the gel network becomes more rigid due to the formation of new Silicate bonds. As these Silicate bonds form the gel contracts. Syneresis accounts for the shrinkage of the gel and the excess water exuded from the gel pores due to the shrinkage [5].

Coarsening or “Ostwald ripening” is the process by which the average pore size of the gel increases and the specific surface area decreases. Convex surfaces are more soluble than concave surfaces. Therefore, when the gel is immersed in a soluble liquid, dissolved material will move to regions of negative curvature. This causes the necks between particles to grow and the filling of small pores, resulting in an increase in average pore size. Segregation is the development of inhomogeneities throughout the gel. An example of segregation is the diffusion of alkali out into the expelled liquid during syneresis [5].

It has been shown experimentally that the syneresis contraction rates increase with temperature [5]. The gelation rate also increases with temperature since syneresis and gelation processes are a result of the same condensation reactions (formation of Silicate from two SiOH groups). If syneresis and gelation rates are increased, aging time will decrease, which is an important part of aging optimization. The gel can be maintained at a high temperature by exposing the alcogel to a flow of heated aging fluid. Ensuring that the gel temperature remains relatively high during aging would reduce aging time. Once the gel is fully aged, it may be supercritically dried to form an aerogel.

3.1.2 Supercritical Drying

Before Kistler successfully created the first aerogel by supercritical drying, gels were dried by evaporating the liquid in air. "The formation of liquid-vapor interfaces within the gel network resulted in surface tensions which caused considerable shrinkage upon drying due to partial collapse of the network [1]." Shrinkage stopped when the gel structure became strong enough to withstand the high tensile strength of the liquid. The remaining collapsed structure is known as xerogel.

In 1931 Kistler [1] successfully remove the liquid from a wet gel by pressurizing the liquid to levels greater than the vapor pressure. Once the liquid was pressurized, he slowly raised the temperature of the liquid until it reached the critical temperature and transformed into a gas. The liquid was never allowed to enter the two phase region and the gel dried with little to no shrinkage. This process is known as supercritical drying. Once the gel is supercritically dried, the structure is porous and sponge like with pores with sizes the order of 1-100 nm [1], which provides excellent insulation properties.

Industry has capitalized on aerogel's beneficial properties, especially in the field of insulation. In particular, aerogel insulation blankets have evolved as a versatile product for many insulation applications. This work aims to decrease aging time during manufacturing of these aerogel blankets. Thus, certain aspects of the manufacturing process must be understood.

The manufacturing of alcogel blankets (pre-dried aerogel blankets) consists of four steps including casting, chemical aging, supercritical extraction, and heat treatment. During casting a mesh separator is rolled with an alcogel blanket. The resultant geometry is a large roll consisting of alternating layers of alcogel blanket and mesh separator as seen in figure 3.1. The mesh separator creates a flow channel between each layer of alcogel through which heated aging fluid may flow. It has been shown that aging time can be reduced by maintaining uniform flow of aging fluid between the alcogel layers [2]. Therefore, a mesh separator will be designed to maintain uniform flow and optimize aging time. In order to replicate flow conditions between the alcogel roll layers for laboratory testing, a simpler model of the roll must be developed.

3.2 Roll Geometry Simulation

The gel rolls created in industry are quite large (approximately 5' long and 3' in diameter) and must be scaled down for laboratory experiments. The flow process of concern is that of the aging fluid between the roll layers. The flow between the roll layers can be represented as an annular flow since the alcogel layers form concentric rings through which aging fluid flows. The height of the flow channel (H) created by the mesh separator is very thin in comparison to the gel layers and it can be assumed that the radius of the inner layer approaches the radius of the outer layer.

$$\frac{R_{inner}}{R_{outer}} \approx 1 \tag{3.1}$$

When this occurs the flow can be approximated as flow between parallel plates (See Figure 3.1). The simplified geometry eases replication of the flow system in the laboratory significantly.

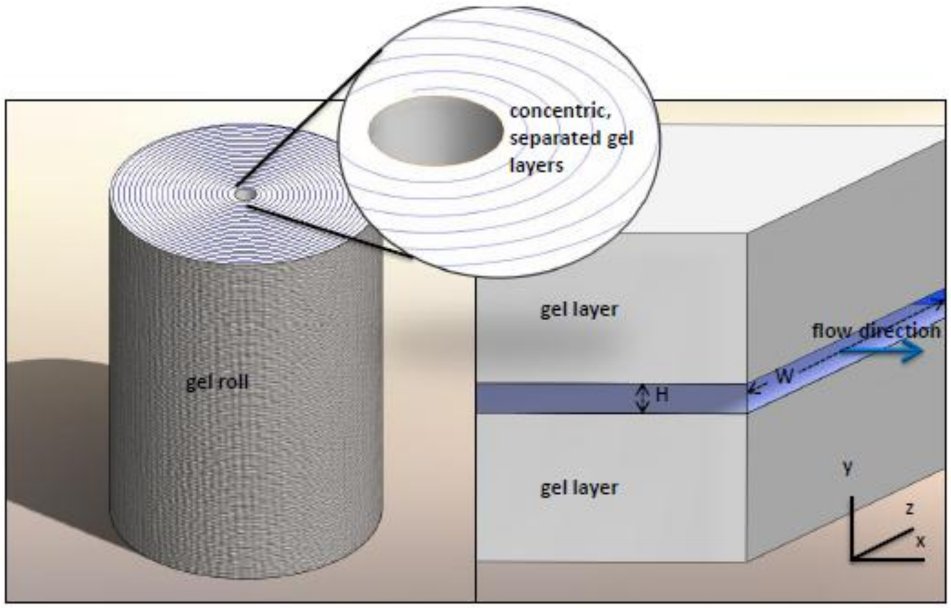

Figure 3.1 Annular Flow Approximated as Parallel Plate Flow [4]

Several assumptions must be made to model flow between the roll's alcogel layers. The assumptions simplify the Navier-Stokes equations, which are used to derive the velocity profile for flow between parallel flat plates. The following assumptions are made: the flow is driven by a pressure gradient and no other outside forces; the flow is fully developed and steady; the flow is incompressible; the dynamic viscosity of the aging fluid remains constant; there's no velocity gradient in the x and z directions; the walls are impermeable and there's no flow in the y and z direction; there's a no-slip condition at the walls, which requires the velocity to be zero at the walls; the effects of gravity are negligible; and there are no pressure gradients in the y and z direction. All of these assumptions allow one to reproduce manufacturing conditions in the laboratory using a parallel plate configuration. Even though the model is simplified, it provides a reasonable representation of actual flow conditions.

An experimental set up is designed with the above assumptions and flow conditions in mind and will be discussed in Chapter IV. However, before discussing how the simplified model is implemented in our experiments, it is important understand all prior work that addresses similar problems.

3.3 Prior Research

A significant amount of research has been completed on two subjects that are closely related to the scope of this work: stress distributions in spiral wound rolls and mesh separators for ultrafiltration applications. Useful information was obtained from prior research involving these subjects and utilized to improve laboratory experiments.

As previously stated, this work aims to optimize the flow of aging fluid between alcogel roll layers. Interlayer pressures within the wound alcogel roll may drastically affect flow behavior. Therefore, it is important to understand the interlayer stress distributions in spiral wound rolls in order to accurately reproduce manufacturing flow conditions in the laboratory.

Additionally, a mesh separator is used to keep the alcogel roll layers separate and to create a flow channel for aging fluid during the aging process. A similar approach is used in ultrafiltration processes but with a different end goal. In ultrafiltration applications the mesh separator is optimized to enhance permeate flux through a membrane, or in other words mass transfer mechanisms, whereas our mesh separators will be optimized to enhance convective heat transfer between the aging fluid and the alcogel layers. However, understanding the optimization techniques used for mesh separators in ultrafiltration applications may elucidate relevant methods for optimizing mesh separators to enhance the flow of aging fluid between alcogel layers.

Several research papers addressing stresses in spiral wound rolls and ultrafiltration processes have been summarized to divulge information that may enhance laboratory experiments. Literature addressing stress distributions in spiral wound rolls is discussed first and mesh separators in ultrafiltration applications second.

3.3.1 Modeling Stresses in Spiral Wound Rolls

Stress distributions within spiral wound rolls have been modeled by many researchers. Analysis of initial wound roll stresses began with Gutterman in 1959 [7] and Altmann expanded on Gutterman's analysis in 1968. Altmann characterized each roll layer as a linearly elastic, which allowed him to derive a set of integral equations that predicted interlayer pressures and in-roll tensions [8]. Each model thereafter was adjusted to accommodate a specific problem, or to produce more accurate results.

For example, R. C. Benson [9] created a non-linear wound roll model that allows for large deformations within the roll. No prior papers addressed the issue of roll deformations.

W. R. Qualls and J. K. Good [10] developed an orthotropic viscoelastic winding model including a nonlinear radial stiffness, and were the first to couple "the nonlinear orthotropic attributes of a wound roll with a complex viscoelastic constitutive relation." Varied models of the stress distribution within spiral wound rolls were produced, but all show similar trends (See Figure 3.2): high interlayer pressures at the center of the roll which decrease as the distance from the roll center increases.

The variation in interlayer pressure for spiral wound rolls requires consideration when designing the optimum separator. A separator designed to withstand interlayer pressures similar to those toward the edge of the spiral wound roll may not withstand higher interlayer pressures similar to those near the center of the wound roll. The separator must be able to withstand a wide range of interlayer pressures and tests should be completed to determine which separator system has this versatility. Designing a mesh separator which withstands these variant interlayer pressures in spiral wound rolls was not the focus of this research. However, it is recommended that interlayer pressures be considered in future work addressing the optimization of mesh separators in spiral wound gel rolls.

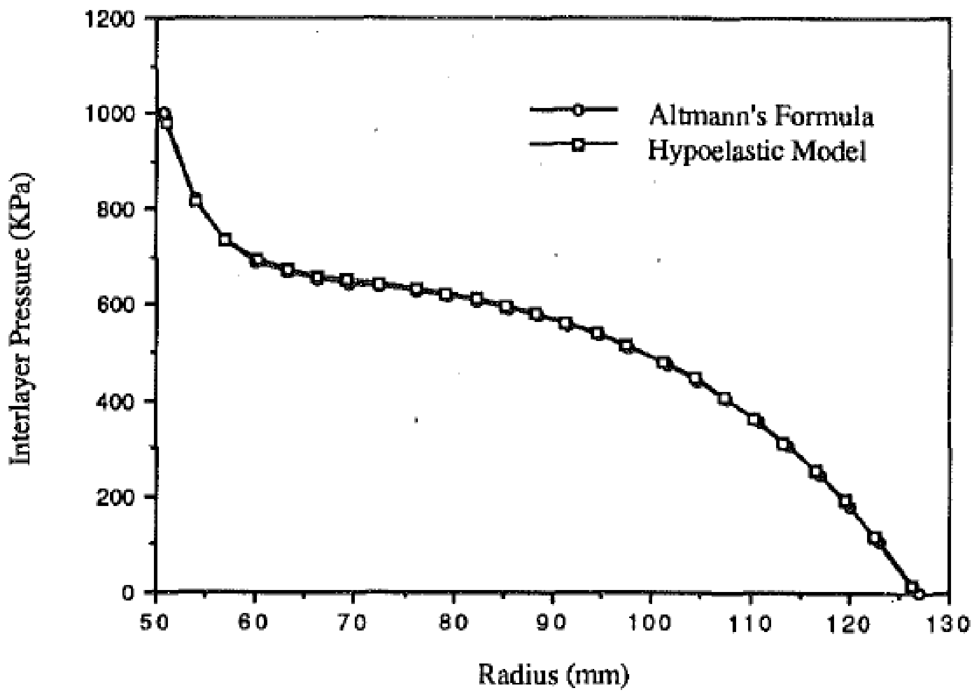

Figure 3.2 A Comparison of Zabaras et al.'s Hypoelastic Model To Altmann's Formula for a Orthotropic Tape Pack [11]

3.3.2 Mesh Separators

Most prior research involving mesh separators concerned itself with designing and optimizing the ideal mesh spacer for ultrafiltration (UF) systems, which are quite similar to the systems studied in this work. The main difference between the two systems is the Biot number. UF processes result in low Biot number systems whereas flow between alcogel layers result in high Biot number systems as discussed in Chapter I [4]. Additionally, mesh separators are optimized to enhance mass transfer in UF applications, whereas this work will optimize mesh separators to maintain uniform flow between alcogel roll layers. Mesh separators and their effect on UF have been researched extensively. “The major problems for UF processes are concentration polarization and fouling which both reduce flux [12].” Prior research determined that one may diminish or eliminate these problems in UF processes by optimizing the mesh separator.

In 2003 Schwinge, Wiley, and Fane [12] studied the effects of spacer mesh length, filament diameter and filament orientation on flux in great detail. The experiments revealed that “when spacer filaments are adjacent to the membrane, reducing mesh length leads to an increase in the flux until a large portion of the membrane area is covered by filaments which reduces permeate production.” Schwinge et al used this knowledge to design an ideal spacer which imposes high mass transfer rates and low pressure drops across the flow channel.

They developed an advanced 3-layer spacer (A3LS) with superior mass transfer characteristics and less fouling propensity when compared with conventional 2-layer spacers. Three overlapping strands create the A3LS and two overlapping strands create the two layer mesh spacers. The A3LS did increase pressure loss across the channel but there was still an economic advantage to using the A3LS.

In [12] the spacer height is increased by layering additional strands. A similar approach was successfully implemented in this research (as discussed in Chapter V), the difference being that multiple meshes were layered on one another instead of layering additional strands in a single mesh spacer. Work completed in [12] indicated a layered system would increase pressure drops. However, it was believed that a layered system would provide several other advantages, which would compensate for the increased pressure drop.

In 2002 Li, Meindersma, Haan, and Reith [13] ran Computational Fluid Dynamic (CFD) simulations to determine mass transfer coefficients and power consumption of commercial net spacers for low Reynolds flows in flat channels. There are two types of commercial net spacers typically used: woven and non-woven (See Figure 3.3). [13] only simulated the non woven spacer since the simplified geometry facilitates CFD simulation. "The simulations show transversal and longitudinal vortices, vortex shedding and instable flow behavior."

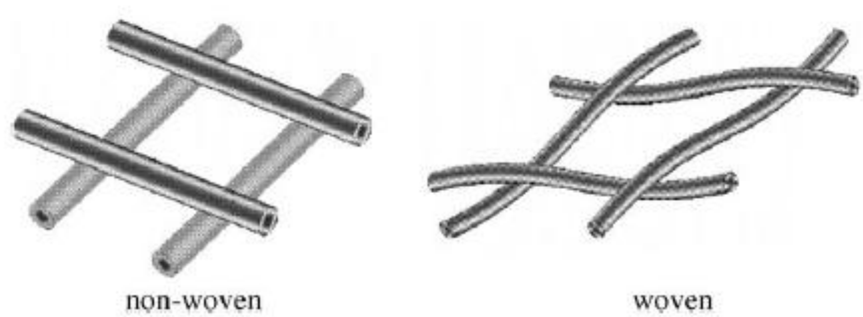

Figure 3.3 Non-Woven and Woven Spacer [13]

Work completed in [13] found that an optimum mass transfer coefficient can be obtained by adjusting certain geometric characteristics: l/h, α, and β (See Figure 3.4). In [13] good agreement was found between CFD results and experimental data reported in literature, along with good agreement between simulated empty channel data and theory. The CFD simulations were also validated by a few experiments discussed in [13].

The models developed in [13] utilized CFD simulations to determine mass transfer coefficients, but future CFD simulations may be able to determine the pressure drops induced by the mesh separator. We know that the pressure drop will increase with higher levels of obstruction, but the effect of obstruction orientation and geometry on pressure drop has not been studied using CFD simulations. Understanding the effect of mesh geometry on pressure drop would be very helpful when choosing the best mesh separator for the flow process studied in this work. However, in this work instead of running CFD simulations, pressure drop tests were completed for various geometries and layered schematics to determine the best separator for flow between alcogel layers.

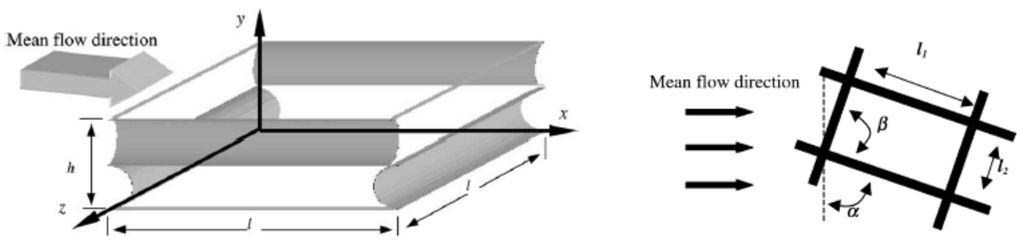

Figure 3.4 Geometry of a Non-Woven Commercial Net Spacer [13]

In 1993 Da Costa, Fane and Wiley [14] developed a correlation that allows the characterization and design of net-like feed channel spacers in any combination of geometric characteristics: angle, mesh size, thickness, strand size, and voidage. “Flow visualization and pressure drop experiments have shown that the hydrodynamic angle θ is the most important parameter which can be used to describe fluid flow in spacer filled channels (See Figure 3.5) [14].”

Da Costa et al. developed a pressure drop model which showed that friction losses at the channel walls and on the spacer surface were very small. Form drag from spacer strands and kinetic losses due to change in direction of flow were found to be the dominant contributors to pressure drop. Research in [14] used a modified Grober equation to model mass transfer in the spacer filled channel. “The pressure drop and mass transfer models were used to predict spacer behavior in ultrafiltration at varying angle and voidage [14].”

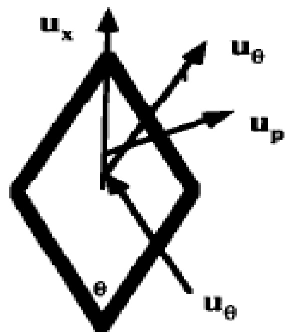

Figure 3.5 Representation of Mesh where the flow runs Parallel to the x-axis [14]

In 1991 Da Costa, Fane, Fell, and Franken [15] examined the effect of spacer design on flux, mass transfer, and pressure loss for typical UF conditions. They performed UF experiments with a Dextran T500 solution in a thin channel filled with various types and orientations of spacers (See Figure 3.6). They found that "feed channel spacers improve typical UF flux by 3 to 5 fold with pressure loss increases of 5 to 160 fold [15]."

Da Costa et al. also found that the mass transfer can be correlated as a laminar flow phenomenon and performance is well predicted by the Grober equation, where L is the spacer length and d_h is the hydraulic diameter.

$$Sh = cRe^a Sc^b \left(\frac{d_h}{L}\right)^d \tag{3.2}$$

Additionally, [15] found the following relationship between pressure loss and flow rate (Q): $P_{loss} \propto Q^{1.8}$. This indicates there are "turbulent flow phenomena or losses dominated by the characteristic angle of change in flow direction induced by the spacers." Essentially mass transfer effects are controlled by the flow region close to the membrane, while pressure losses are dominated by energy losses induced by the spacer. It must be noted that both flux and pressure loss increase with characteristic angle.

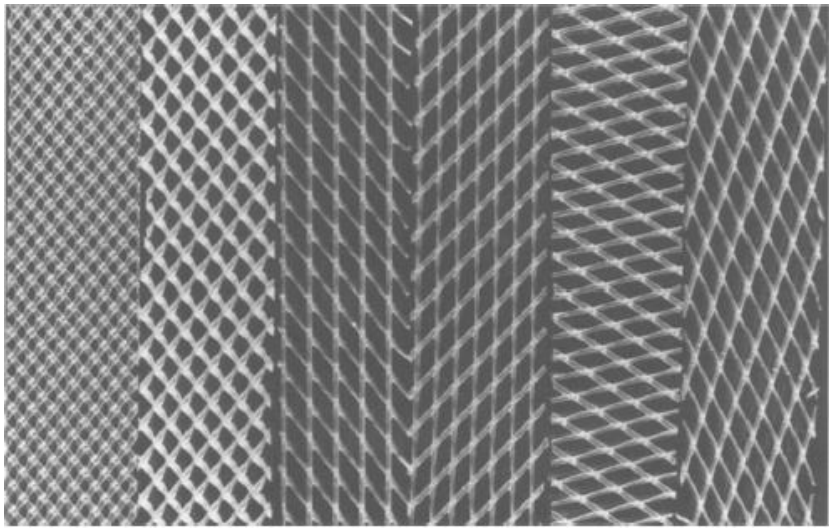

Figure 3.6 Examples of Spacers [15]

There are great similarities between the work completed in [14], [15] and this thesis work. Da Costa et al. completed pressure drop tests for low Biot number systems, which demonstrated that pressure drops were "dominated by energy losses induced by the spacer." In this work pressure drop tests were also conducted for various mesh separators. Results obtained in [4] indicated a form drag term induced by the spacer was the dominant contributor to pressure drop, verifying the work completed in [14] and [15]. Only the heat transfer characteristics changed from the ultrafiltration systems studied in [14] and [15], not the physical interactions between the separator and the fluid.

The research completed in [12], [13], [14], and [15] investigated ultrafiltration processes. All of them aimed to optimize permeate flux through a membrane by studying and understanding the interactions between the mesh separator and the membrane. In all cases, the mass transfer coefficient was the property of greatest concern. This recent work is less concerned with mass transfer properties and, instead, aims to optimize heat transfer characteristics of flow processes in a similar system in order to reduce aging time. Once again, heat transfer between the heated aging fluid and the alcogel blanket can be increased by designing a mesh separator capable of maintaining uniform flow of the heated aging fluid between the alcogel roll layers. Given our understanding of the research completed for ultrafiltration processes and stress distributions in spiral wound rolls, we may develop an accurate and informative experimental set-up and procedure for laboratory testing.

Chapter IV

APPROACH

Manufacturing processes currently used in industry to produce aerogel insulation blankets consume significant amounts of energy due to lengthy aging and supercritical drying times. Aging time can be reduced by maintaining uniform flow of heated aging fluid between the alcogel roll layers during aging. Uniform flow may be maintained by optimizing the mesh separator, which is rolled within the alcogel roll. The work discussed in this thesis focused on this optimization. In order to determine the best mesh separator configuration to maintain uniform flow under manufacturing conditions, pressure drop tests were completed at various flow rates for several separators and separator systems layered between alcogel blankets. Flow conditions between the alcogel layers during aging were reproduced in the laboratory using a scaled parallel plate configuration designed in [4] (See Figure 4.3 and 4.5).

It is important to note that all tests completed in [4] utilized a solid polycarbonate plate as the upper and lower boundary (See Figure 4.3). In actual manufacturing processes the aging fluid flows through a spacer separating alcogel layers. Experiments completed in this work replicated actual manufacturing processes. Initially, surrogate materials for the alcogel blankets were researched to avoid complexity of the alcogel preparation process. Unfortunately, no surrogate material could be found to accurately reproduce the effects of the composite alcogel blanket. The decision to use alcogel blankets over a surrogate material is discussed later in this chapter, and it must be noted that all experiments were, in fact, completed with composite alcogel blankets placed on either side of the mesh separator.

For safety, water at room temperature was used instead of heated aging fluid in all pressure drop experiments. The flow rates tested were in a range of Reynolds numbers matched to the Reynolds number flows used in industry. The flows needed to be matched via Reynolds number because the aging fluid's viscosity is different from that of water. The set up allowed for variable flow rates and spacer heights (See Figure 4.3). It was extremely adaptable and very useful when testing different separator configurations. A detailed experimental procedure was followed for all pressure drop experiments and can be seen in Appendix B.

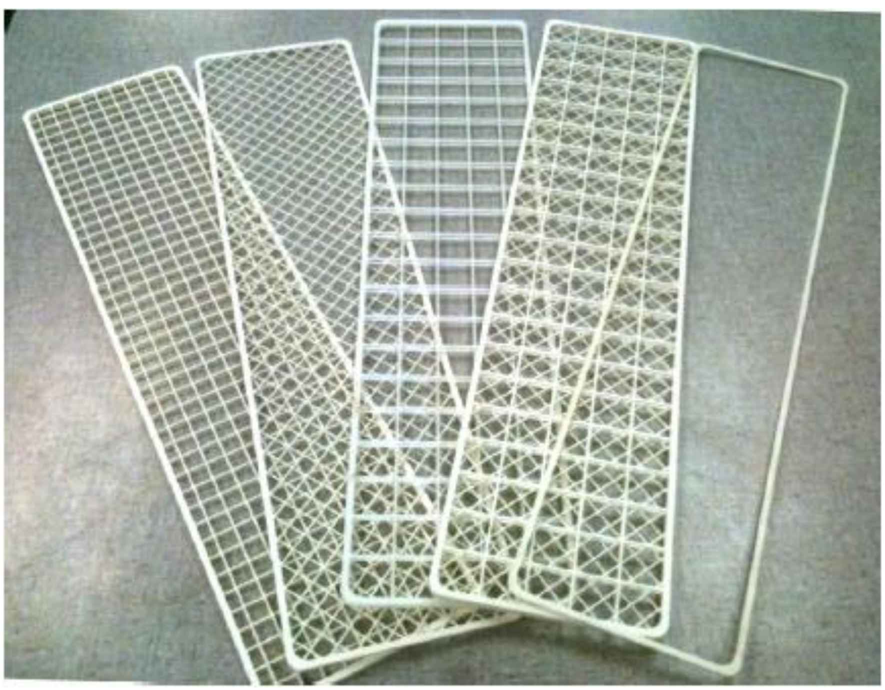

Figure 4.1 Various Mesh Separators (From Left to Right: Fine Perpendicular, Fine Diagonal, Posted Perpendicular, Caged Diagonal, and Open Channel) [4]

Flow between alcogel layers can be modeled as plane-Poiseuille flow. Therefore, the experimental set up was validated by comparing experimental results to theoretical values of pressure drop for the plane-Poiseuille case (flow between two flat plates). After validation, pressure drop experiments were run for several layered and un-layered separator designs. Ten separators were tested in all (See Figure 4.1, Figure 4.2, and Appendix A). The following sections give detailed explanations of the experimental set-up, validation of the experimental set-up, the various layered schematics used during testing, and the measurements taken that led to the decision to use alcogel over a surrogate material.

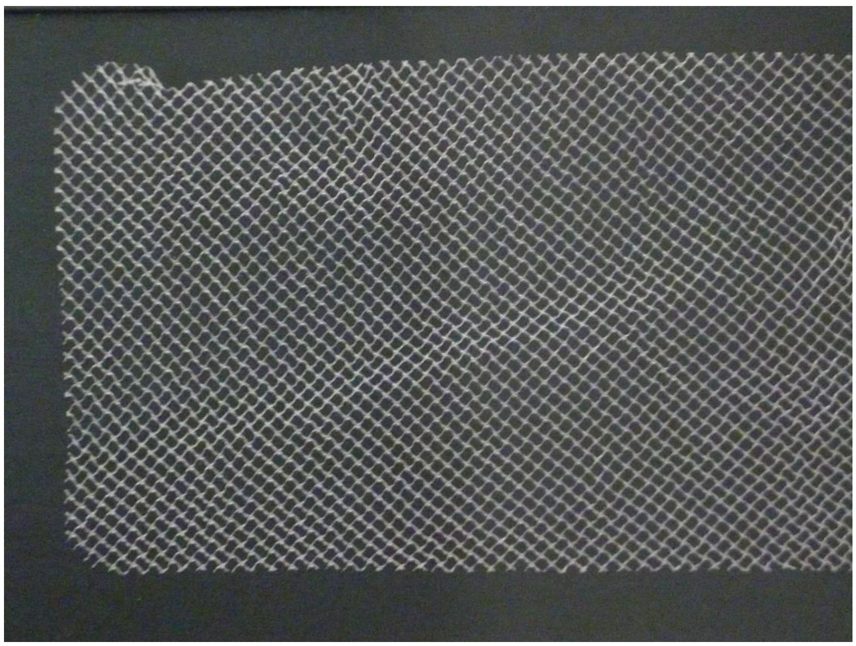

Figure 4.2 Net Mesh Used in Industry

4.1 Experimental Set-Up

The experimental set up imitates flow conditions of the gel manufacturing process in order to ensure the data produced is relevant and useful. The flow channel is designed to allow measurement of the pressure drop of a fluid flowing through a channel (See Figure 4.3). Both plane-Poiseuille and obstructed flows can be tested by inserting mesh separators of varying height and obstruction level into the channel. The set-up also allowed the insertion of additional layers of mesh, alcogel, and other sheet materials. The channel’s variable height was an extremely important aspect of the design since alcogel slabs were layered on either side of different mesh separators to best imitate the flow conditions of the manufacturing process.

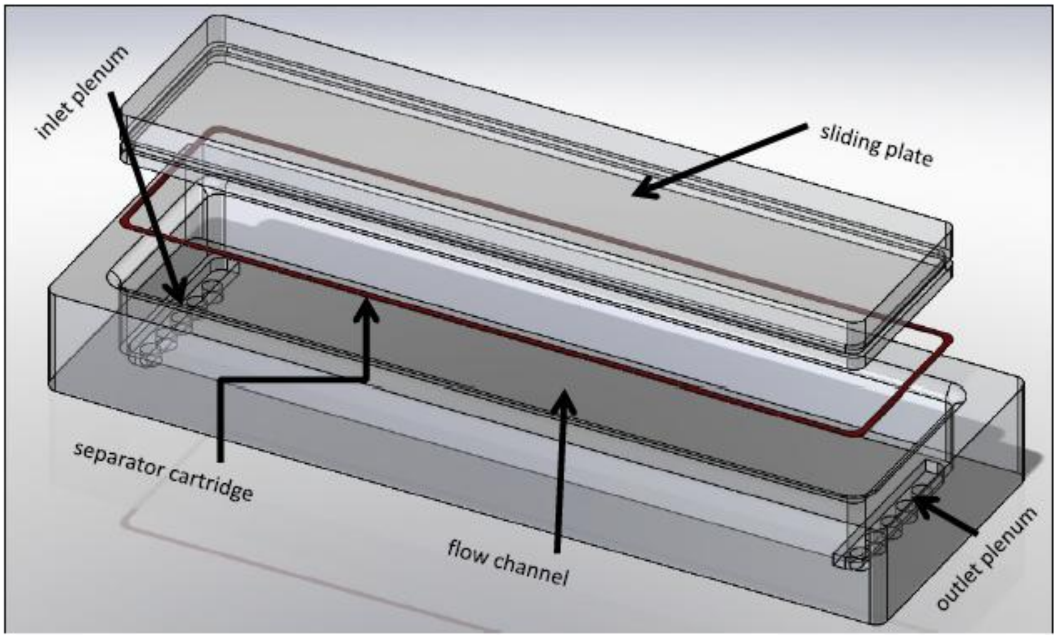

Figure 4.3 Experimental Flow Channel [4]

Included in the set up is a high precision positive displacement gear pump, the Ismatec MCP-Z Standard, which pumps fluid from a recirculation tank through the flow chamber and back to the recirculation tank. The pump has a stepper motor, programmable interface, and a non-pulsating flow [4]. All of these qualities are crucial when establishing steady state flow through the flow channel.

A Setra Model 230, wet to wet pressure transducer is used to measure pressure drop across the flow channel. Pressure lines run from the high and low pressure side of the flow chamber to the respective ports of the transducer. The transducer is capable of measuring 0 to 13790 Pa differential pressure and has a tolerance of +/- 0.25%. The transducer is wired to a data acquisition system for signal interpretation.

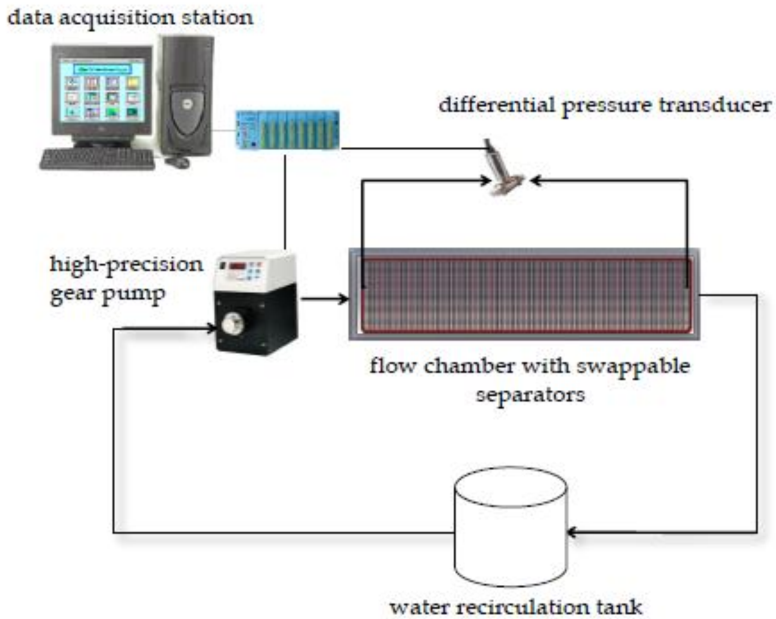

Figure 4.4 Systems View of Experimental Set-Up [4]

A 4 to 20 mA signal is sent from the transducer to a NI 9203 Analog Input Module, which is connected to a NI cDAQ-9174 USB chassis. The signal is relayed from the chassis to a user controlled LavVIEW program, which translates the signal to pressure drop. The program then records and displays differential pressure. For example, a 4 mA signal outputted from the transducer translates to 0 psid and a 20 mA signal translates to 2 psid. The differential pressure reading is recorded to a txt file and displayed in real time on the computer monitor as a plot of differential pressure versus time. A systems view of the whole experimental set up can be seen in Figure 4.3.

4.2 Validation of Experimental Set Up

Before we began testing, the experimental set-up needed to be validated. The best way to ensure the set up measured pressure drop accurately was to compare experimental results of a well known and studied case, plane-Poiseuille flow, to theoretical results. Plane-Poiseuille flow, or flow driven by an externally imposed pressure gradient between flat plates, has been thoroughly researched [16] (See Figure 4.5).

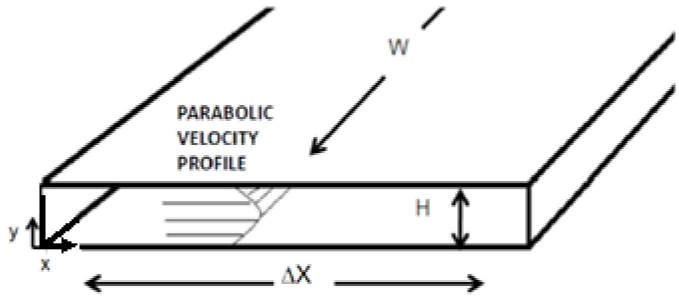

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Figure 4.5 Plane-Poiseuille Flow [4]

The equation for plane-Poiseuille flow is derived from the continuity and Navier Stokes momentum equations. Solving these equations yields the following formula for the velocity profile for flow between parallel plates [17]:

$$u = \frac{y}{2\mu}\frac{dp}{dx}(y - H) \tag{4.1}$$

The experimental set up allows pressure drop to be measured for various volume flow rates. In order to develop a comparison between experimental and theoretical results, the theoretical volume flow rate through the plates can be determined by evaluating the following integral over the cross sectional flow area:

$$Q = \iint u \cdot dz \cdot dy \tag{4.2}$$

Evaluating the integral yields:

$$Q = \frac{H^3 W}{12\mu}\frac{dp}{dx} \tag{4.3}$$

Since the pressure gradient is constant we can set dp = Δp (change in pressure) and dx = L (length of channel). Rearranging equation 4.3 and solving for pressure drop gives:

$$\Delta p = \frac{12Q\mu L}{H^3 W} \tag{4.4}$$

Equation 4.4 gives the theoretical pressure drop across the channel and can be evaluated for various flow rates. Comparisons between theoretical and experimental pressure drops for various flow rates can be made to determine the validity of the experimental set up.

It must be noted that theoretical plane-Poiseuille flow is laminar. All experimental measurements of pressure drop must be made for flow rates within the laminar regime, Re < 1500. The Reynolds number is used to determine the maximum flow rate that may be measured [18] where D_H is the hydraulic diameter, U is the average fluid velocity, ρ is the fluid density, and μ is the dynamic viscosity.

$$Re = \frac{\rho U D_H}{\mu} \tag{4.5}$$

Setting Re = 1500, and plugging in values for D_H, ρ, μ allows one to solve for the average fluid velocity, U. The volume flow rate, Q, is equal to the average fluid velocity times the cross sectional flow area as seen in equation 4.6.

$$Q = UA \tag{4.6}$$

Equation 4.6 can be used to solve for the maximum volume flow rate that ensures laminar flow (Re < 1500). In this instance, the maximum flow rate that may be used is 0.225 m^3/s. This value was determined using the following properties of water: $\rho = 1000\ kg/m^3$, $\mu = 1.15 \times 10^{-3}\ N{\cdot}s/m^2$. The highest flow rates used in all of the completed tests did not exceed $33.3 \times 10^{-6}\ m^3/s$, which guaranteed all tested flows were in the laminar regime and experimental results could be compared to theoretical plane-Poiseuille flow.

4.3 Reproducing Manufacturing Conditions

In order to accurately reproduce manufacturing flow processes in laboratory experiments, one must fully understand conditions throughout the roll during the aging process. Temperature data gathered at various locations throughout the roll displays extreme variation and indicates different areas of the roll are less exposed to heated aging fluid (See Figure 4.6).

Figure 4.6 shows data obtained from industry processes during aging. The depicted information leads one to believe that the current mesh separator does not maintain uniform flow of aging fluid between the roll layers. If this does not occur, the blanket will not heat uniformly as seen in Figure 4.6. As a result, the variation in temperature throughout the roll prevents the alcogel blanket from aging uniformly. This is a clear indication that a mesh separator needs to be designed to maintain uniform flow of aging fluid and allow uniform aging.

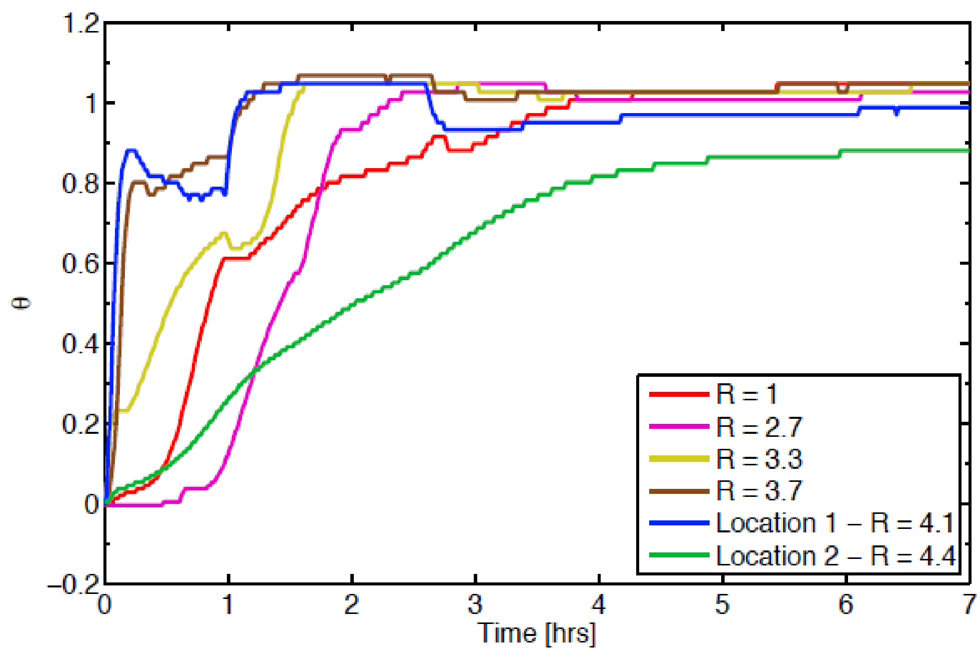


Figure 4.6 Temperature at Various Locations in Alcogel Blanket [2]

Currently, the thin mesh separator is compressed between two, low modulus alcogel layers and merely acts to keep the alcogel layers separate without creating a flow channel for the heated aging fluid. The high interlayer pressures force the alcogel to penetrate into the flow gap and block the flow of aging fluid. There are inconsistencies in roll shape and interlayer pressure, which introduce large gaps or crevices through which aging fluid can flow. However, these intermittent flow gaps and channels are a result of rolling processes and not introduced by or benefits of the mesh separator. To reproduce these effects using the experimental set-up described in section 4.2, alcogel blankets were layered on either side of a mesh separator within the experimental flow channel and clamped in place.

4.3.1 Choice of Alcogel Over Surrogate Material

Alcogel recipes require close attention to detail. Additionally, handling procedures must be followed precisely when producing and using alcogels, which introduce complexity to the experiment. Therefore, a surrogate material with similar mechanical properties to that of an alcogel was preferred for laboratory experiments. The robustness of a non-gel material would be beneficial when conducting and repeating many tests. Essentially, when using alcogel as opposed to a surrogate material, new test alcogel blankets would need to be created for every experiment. This seemed time consuming and unnecessary if a material with adequately similar mechanical properties could be found.

In order to save time and simplify the experiment, we conducted a search for a surrogate material with similar mechanical properties to that of alcogels ensued. The first property of concern was the Shore hardness. Hardness is defined as a material's resistance to permanent indentation. Hardness can be measured using a Shore Durometer of the appropriate scale. The

00 scale, which measures the hardness of soft gel like materials, was used to determine the hardness of different alcogel samples.

Several hardness measurements were taken of alcogel samples using a Rex Durometer, model 1600, type 00. Results ranged from 0-20 on the 00 scale. These are extremely low hardness levels, indicating the gel is very soft and susceptible to penetration. It would be easy enough to find a gel like material with a similar hardness, but it would not be robust.

It must be noted, that the aerogel blankets created in industry are a composite of both alcogel and fiberglass matting. The surrogate material may have similar hardness properties to that of the alcogel, but it would not have the mechanical strength provided by the fiber matting. To create a material with adequately comparable properties to the alcogel blankets created in industry the surrogate gel would need to be cast with fiberglass matting. Evidently, the introduction of a surrogate material would not simplify the experiment or save time, since the preparation process would be similar to that of preparing a composite alcogel blanket.

Sol-Gel	
<u>Sol</u>	<u>89.17%</u>
Silbond H5	30%
Ethanol	60%
Water	10%
<u>Catalyst</u>	<u>10.83%</u>
Ethanol	94%
Ammonium Hydroxide	6%

Table 4.1 Alcogel Recipe

We selected a composite material consisting of alcogel and fiberglass matting for all our experiments. There are many different recipes that produce alcogels (the pre-dried sol-gel), but the recipe seen in Table 4.1 was used for all experiments requiring alcogel layers.

4.3.2 Advantage of Alcogel Layering

Introducing alcogel layers to the experiment created a testing environment analogous to that of the alcogel rolls manufactured in industry. It was also important that the experimental set-up account for the interlayer pressures incurred within the alcogel roll during manufacturing. Therefore, pressure was applied to the flow channel by clamping the alcogel layers tightly on either side of the mesh separator.

Ideally, the exerted pressure would have been measured. This would allow one to determine the precise roll conditions produced by the applied pressure. As previously discussed in Chapter III, the interlayer pressure varies throughout the roll diameter. High interlayer pressures are seen towards the center of the roll, which decrease towards the outer radius of the roll. The conditions produced in the laboratory represent a variety of roll locations depending on the applied force. When performing our experiments we tried to apply a uniform load along the length of the channel. However, our experimental set-up was not equipped with sensors capable of measuring the exact applied pressure and no pressure measurements were taken in the scope of this work. However, it is recommended that future experiments include interlayer pressure measurements.

One could measure the force applied to the layered system in several different ways. The system could be clamped until the system compresses a set amount. The set displacement would known and the internal stress determined using the elastic modulus of the alcogel blanket material and the following equation where σ is the applied stress, δ is displacement, E is the modulus of elasticity of the alcogel blanket and L_o is the thicknesses of the system before the compressive stress was applied:

$$\sigma = \frac{\delta E}{L_o} \tag{4.7}$$

This method would produce some uncertainty. The alcogel blanket properties will vary from sample to sample. Additionally, the elastic modulus varies quite a bit from sample to sample throughout the aging process [19]. The calculated stress will only be as accurate as the elastic modulus used in the calculation.

Perhaps a simpler way to calculate the stress applied to the layered system would be to insert some type of force gauge within the channel. A force gauge could be placed at each corner of the flow channel to get an idea of the overall stress applied to the layered system. The information obtained by the gauges would not show precise stress conditions for the middle of the channel but they would give the researcher a general idea of the overall pressure applied to the layered system. The best method for determining the stress applied to the layered system has yet to be determined, but the method should be implemented in future experiments.

4.4 Methods for Maintaining Uniform Flow

An ideal separator will keep the alcogel layers separate while also enhancing the flow of aging fluid between the gel layers. In a case with solid upper and lower boundaries, the flow can be enhanced by creating a thicker flow channel or by reducing the obstruction to flow, both of which increase flow rate through the flow channel. Since the alcogel has such a low modulus of elasticity, reducing the obstruction to flow would not result in higher flow rates because the alcogel will penetrate into the flow gap. It seems as if the thicker separators (Fine Diagonal, Fine Perpendicular, Coarse Diagonal, Coarse Perpendicular, all seen in Appendix A) would provide a thicker flow channel (See Table 4.2). However, the alcogel will penetrate into these thicker channels much more easily than it does with the net mesh. A configuration must be found that increases the flow gap without allowing the alcogel to penetrate into the flow channel.

By layering several separators one may obtain the benefits of several different meshes. For instance, a layered separator system consisting of net mesh, thick separator, and net mesh (See Figure 4.7) may provide a thicker flow gap while also preventing alcogel from penetrating into the flow channel.

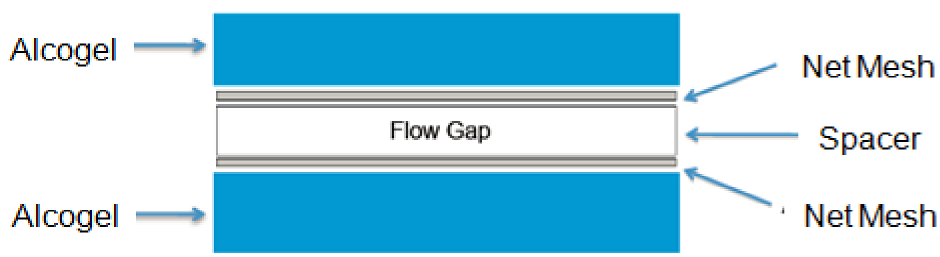


Figure 4.7 Layered Separator Systems

The finer mesh size of the net mesh will prevent the alcogel from penetrating into the flow channel created by the thicker separators (Fine Diagonal, Fine Perpendicular, Coarse Diagonal, Coarse Perpendicular Half Strands). In order to test this hypothesis, pressure drop tests were run for two individual separators and eight layered separator systems with various mesh sizes and layered configurations. Table 4.2 lists thicknesses for each separator used during experiments. The height of each layered system can be approximated by adding each separator height in the system together. Comparison of results, as discussed in Chapter V, determined whether a layered system of separators provided any benefit over a single separator.

Experiments completed in [4] implemented the same experimental set-up and determined the pressure drop incurred by different separator designs when placed in cross flow without alcogel layers. Separators that obstructed flow less were expected to perform better than separators with high levels of obstruction. A clear hierarchy was established which displayed the separator with the lowest pressure drop (See Figure 4.8). The open channel case produced the lowest pressure drops as expected. The next best performing separator was the posted perpendicular and the worst performing separator was the net mesh currently used in industry.

Mesh Separator	**Thickness (mm)**
Net Mesh	0.95
Posted Perpendicular	4.40
Fine Perpendicular	2.20
Fine Diagonal	2.20
Coarse Perpendicular Half Strands	4.40
Very Fine Mesh	0.081
Semi Fine Mesh	0.15
Aluminum Foil	≈0.2

Table 4.2 Thicknesses of Mesh Separators

Analysis of all results revealed both a linear plane-Poiseuille term and a quadratic form drag term contribute to pressure drop across the channel. The form drag term, induced by a separators obstruction to flow, proved to be the dominant contributor to pressure drop. The layered separator tests were expected to produce similar results. Separator systems with high obstruction levels and thinner overall heights were expected to produce the highest pressure drops. Additionally, we thought the separators tested in [4] with a net mesh on either side would follow the same performance pattern seen in Figure 4.8, but at collectively higher pressure drops.

Individual separators (not layered with net mesh) tested with alcogel layers on either side were expected to produce very high pressure drops relative to those obtained in [4] and those expected from the layered system of meshes. In fact, the alcogel was expected to penetrate into the mesh pores and block fluid flow almost entirely, which in turn would produce extremely high pressure drops for relatively low flow rates. Chapter V gives the results obtained for all separator systems tested.

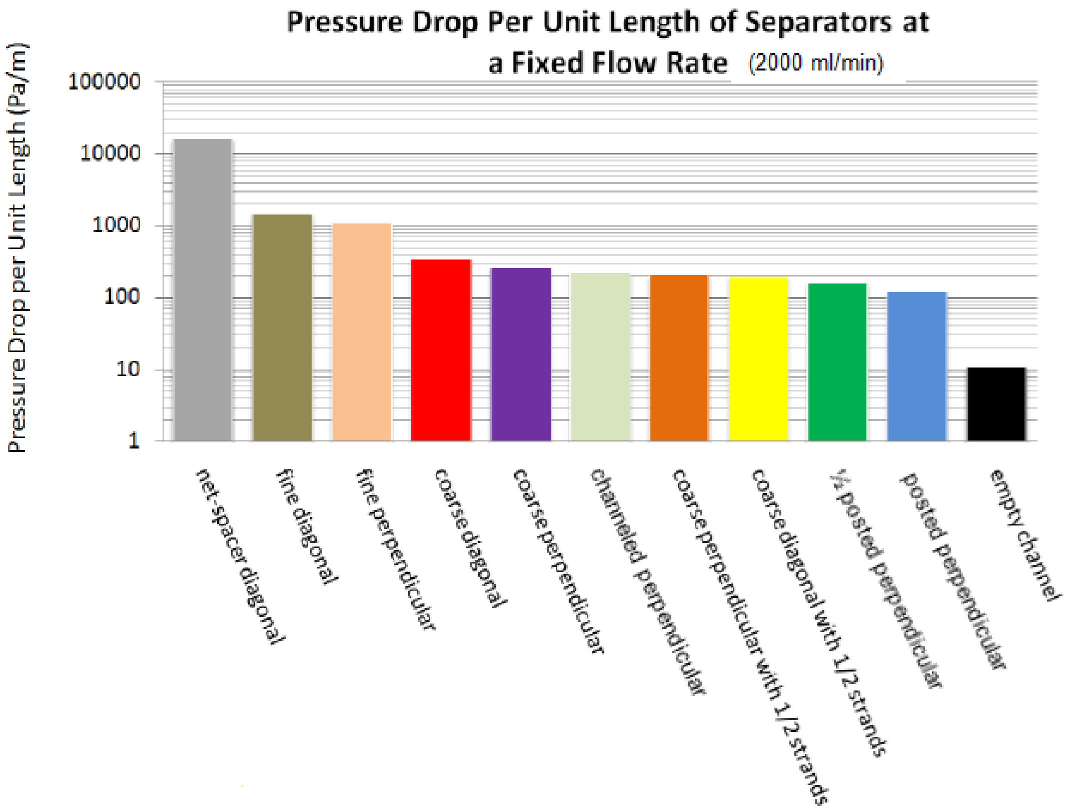


Figure 4.8 Performance Comparison of All Tested Separators [4]

Chapter V

RESULTS

In this chapter we present results obtained for all completed pressure drop experiments. First, results are presented for open channel experiments, which were used to validate the experimental set-up. Next, results are given for two single separators tested with alcogel layers: net mesh and Posted Perpendicular. Lastly, results are presented for the layered separator systems, which consisted of two to three of the following meshes layered in various schematics: net mesh, Fine Perpendicular, Fine Diagonal, Coarse Perpendicular Half Strands, Very Fine mesh, Semi Fine mesh, and aluminum (meshes not depicted throughout the thesis can be seen in Appendix A).

5.1 Validation Results

Before testing any mesh separators the experimental set-up was re-validated by measuring pressure drop across a flow channel for various flow rates. All validation experiments were run with an open channel, parallel plate configuration and the results were compared to theoretical values of plane-Poiseuille flow at the same flow rates. Pressure drop measurements were recorded for flow rates from 3.33×10^{-6} m^3/s to 33.3×10^{-6} m^3/s. The first validation test results were for a flow channel with a height of 0.00205 m (See Figure 5.1). This thickness was chosen because of tolerance constraints and because it is similar to the thickness of the net mesh used in industry, which is 0.00095 m. The length by width dimensions of the flow channel in this test and all following tests were the same at 0.4064 m x 0.1016 m (L x W).

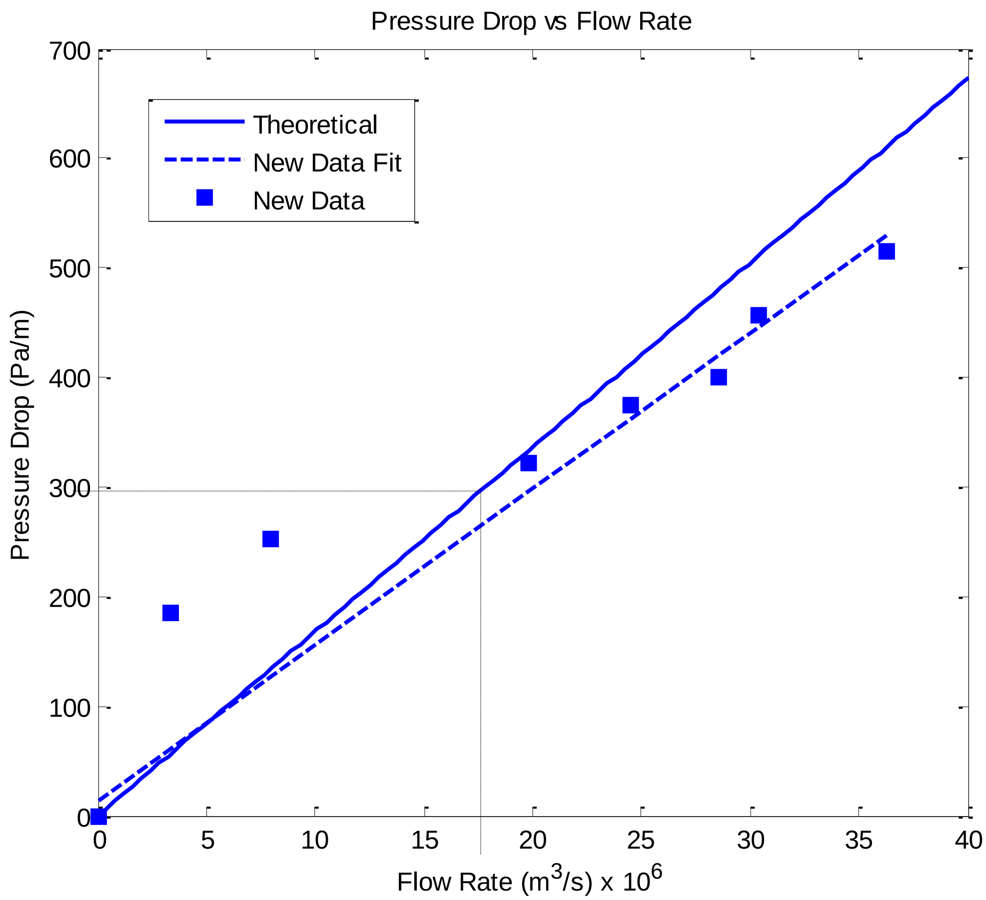


Figure 5.1 Validation of Experimental Set-Up Comparison of Experimental Data to Theoretical Plane-Poiseuille Flow

The pressure transducer used during all experiments could measure pressures ranging from 0 to 2 psid within a tolerance of +/- 0.25%. This is equivalent to a 0 to 13,789 differential Pa range with a tolerance of +/- 34 Pa. Therefore, any differential pressure measurements recorded below 170 Pa may have an error of 20% or more. To ensure accuracy of results, data points below 120 Pa differential pressure or 295 Pa/m (pressure drop per meter for a flow channel 0.4064 m long) are indicated in the figure but were not included when forming a best fit line. However, the point (0 m^3/s,0 Pa/m) was included. Indeed, when the pump was off (0 m^3/s) the pressure transducer read 0 Pa differential pressure. The highest flow rate tested was not much higher than 3.33×10^{-5} m^3/s due to pump limitations. Good agreement was found between the experimental and theoretical results as shown in the following error analysis.

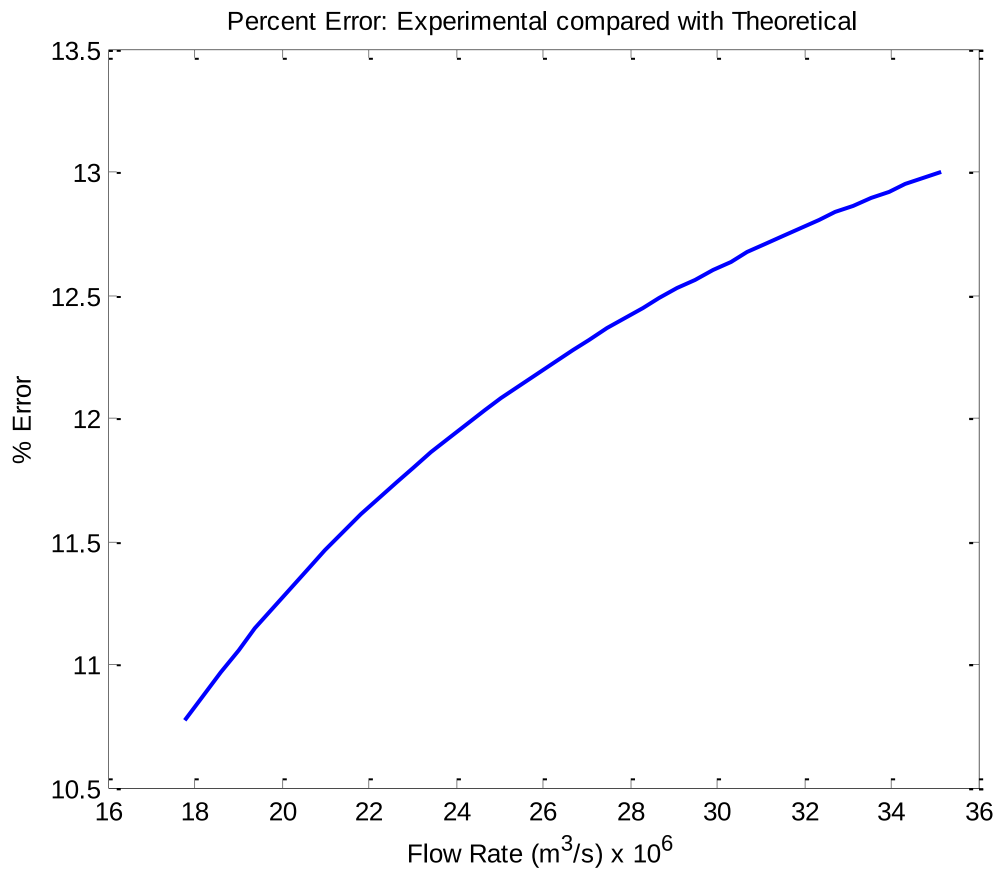


Figure 5.2 Error Between Experimental and Theoretical Results for Plane-Poiseuille Flow

A best fit line of the experimental results was formed using Matlab. The line was fit to data points recorded above a flow rate of 1.76×10^{-5} m^3/s, which corresponds to 295 Pa/m (area enclosed by the two dotted lines is not included to ensure accuracy), and the zero point. The experimental results were then compared to theoretical results using the following formula, which determines the error between the experimental fit line and theoretical values of pressure drop for various flow rates:

$$\% \; error = \frac{|Exp.Val. - Theoretical\,Val.|}{Theoretical\,Val.} \times 100 \tag{5.1}$$

The experimental results align closely the theoretical results. The greatest error found between the theoretical plane-Poiseuille case and the experimental fit line was 13.00% (See Figure 5.2), which indicated the experimental set-up was working as expected. For assurance a mesh separator previously tested in [4] was retested. By testing the Fine Diagonal separator (See Appendix A) we were able to make sure the experimental set-up was working as it did for experiments completed in [4]. Figure 5.3 displays the comparison of the Fine Diagonal results.

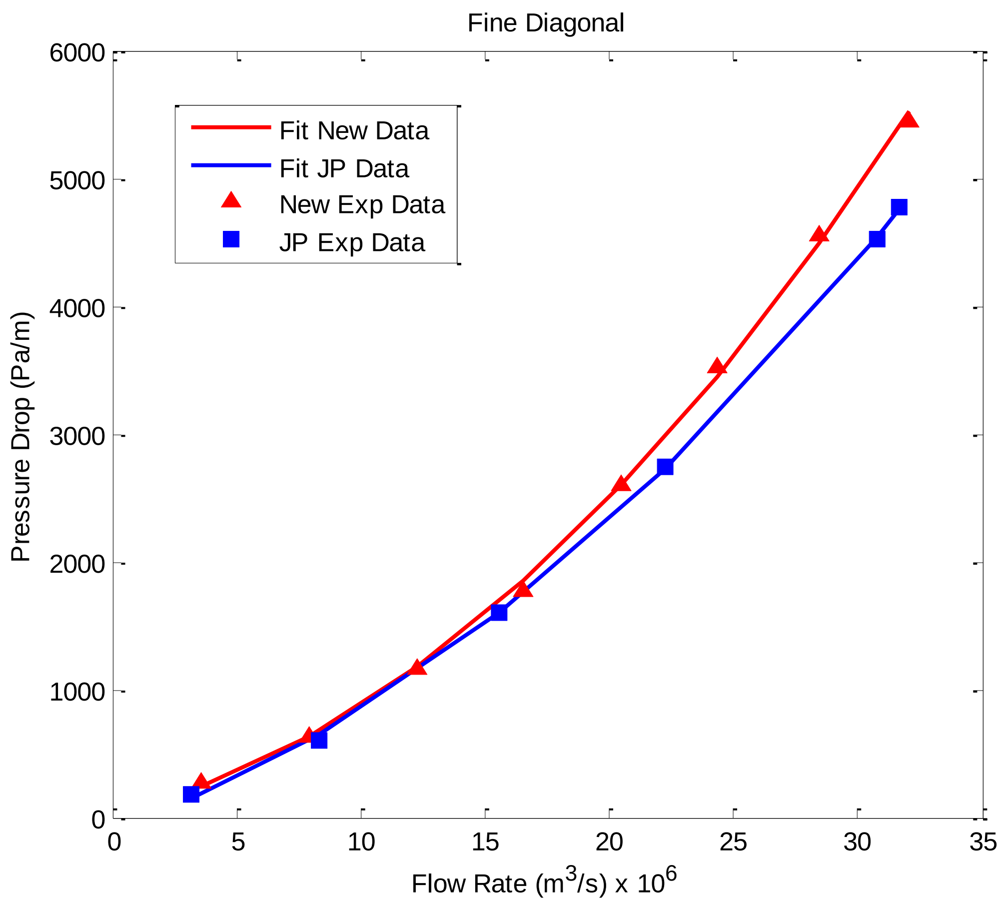


Figure 5.3 Comparison of Fine Diagonal Results
New vs. Prapas

The two sets of results are very similar, but the following formula is used to measure the percent difference between the line fits for each set of results:

$$\% \; difference = \frac{|New\ Val. - Old\ Val.|}{Old\ Val.} \times 100 \tag{5.2}$$

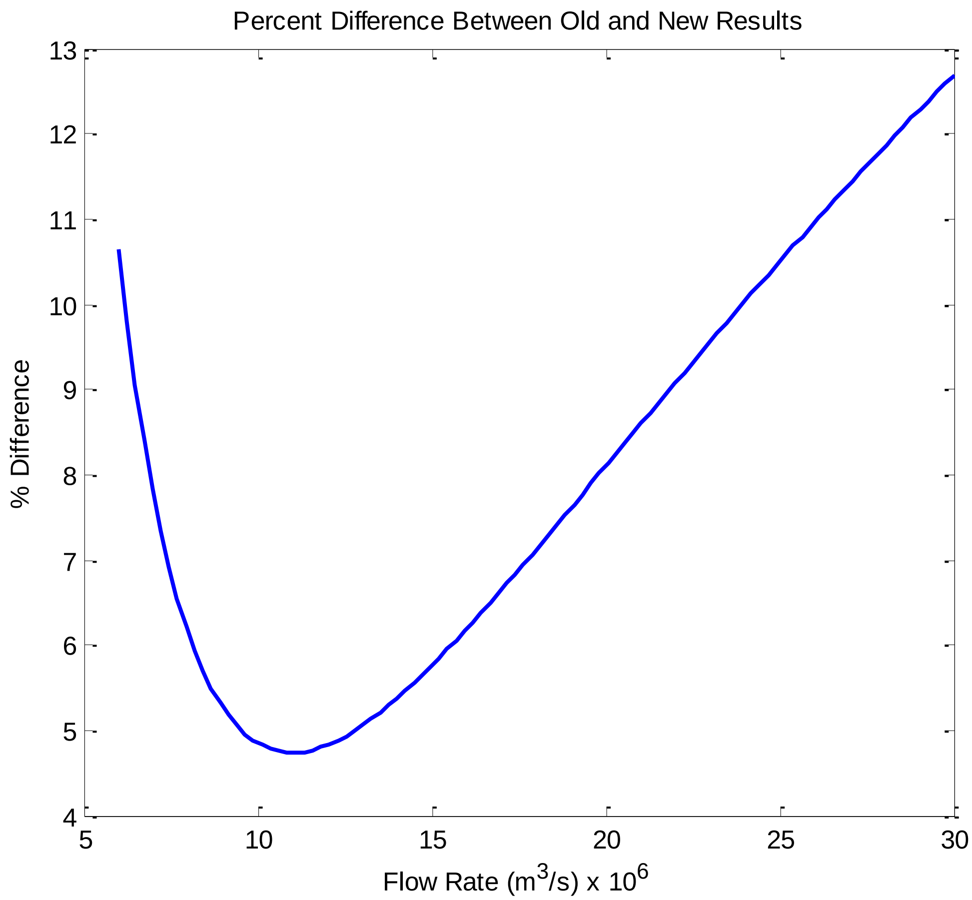


Figure 5.4 Percent Difference between Prapas and New Test Results

In the Fine Diagonal case, only flow rates above 5.83 x 10^{-6} m^3/s produce pressure drops above 369 Pa/m (which corresponds to 170 Pa differential pressure). Therefore, the difference calculation will be completed for flow rates above 5.83 x 10^{-6} m^3/s. Good agreement is found between the two sets of results and the maximum percent difference between the best fit lines for the two sets of results is 14.0%. It occurs at the highest flow rate of 3.33 x 10^{-5} m^3/s as seen on Figure 5.4. The agreement between the two fine diagonal results and the experimental and theoretical results for the plane-Poiseuille case signify a working experimental set-up. Essentially, the set-up has been validated via the outcome of the open channel comparison and the fine diagonal comparison.

5.2 Single Separators in Alcogel

A few single separators were tested with alcogel layers to determine if a single separator could maintain uniform flow of heated aging fluid between alcogel roll layers. First, the net mesh was tested to demonstrate the capabilities of the separator currently used in industry manufacturing processes. The Posted Perpendicular separator was tested next to demonstrate whether a thicker separator with large mesh pore sizes would maintain uniform flow between alcogel layers. The Posted Perpendicular produced the lowest pressure drop of all the separators tested without alcogel layers (See Figure 4.8). It was interesting to see if similar results were produced in tests with alcogel layers. Therefore, results obtained in experiments with alcogel layers were compared to results obtained from experiments completed without alcogel layers [4].

5.2.1 Net Mesh

The first separator tested was the net mesh (See Figure 4.2) currently used in industry manufacturing processes. In this test, composite alcogel blankets were layered on either side of the mesh separator and the layered system was placed in the flow chamber. As previously discussed in Chapter III, roll interlayer pressures can be quite high and may prevent alcohol from flowing through the alcogel layers. In order to replicate the high pressure environment in the wound rolls, the layered system was clamped tightly within the flow chamber. Figure 5.5 shows results obtained for the net mesh with alcogel layers compared to results obtained in [4] without alcogel.

These results seem peculiar at first glance. A quadratic relationship, similar to the test results of the net mesh without alcogel layers, was expected for this obstructed channel flow. However, a linear behavior is evident and the pressure drops measured are much higher than those measured in the plane-Poiseuille and obstructed flow scenarios tested without alcogel layers. The pressure transducer, capable of measuring up to 13,790 psi differential pressure, maxed out at a flow rate below 4.0 x 10^{-6} m^3/s. This was most likely due to two mechanisms: the low elastic modulus, E= 10.4 MPa and Shore hardness level, S < 30-OO, and the formation of two alternate plane-Poiseuille channels.

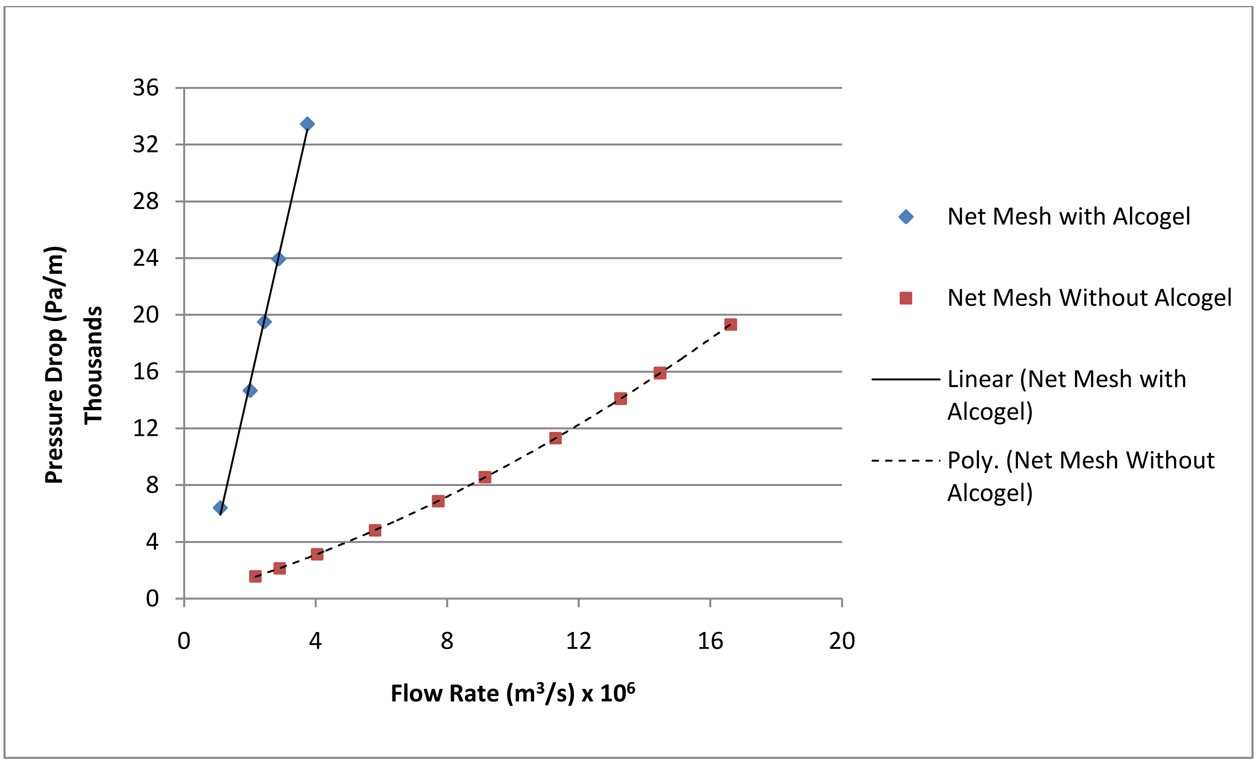


Figure 5.5 Net Mesh with and without Alcogel Layers

The low modulus and hardness of the alcogel allowed the separator to penetrate into the alcogel layers quite easily. In fact, the penetration of the separator into the alcogel seemed to block water from flowing between the layers entirely. If water does not flow between the alcogel layers and through the mesh separator, where does it flow? It flows through the path of least resistance. In this case, the alternate plane-Poiseuille channels formed on the sides of the flow chamber.

The gel layers and separator fit comfortably within the flow chamber with no space between the layer edges and the sides of the channel. However, the alcogel layers were clamped within the flow chamber to ensure high interlayer pressures. Pressure was exerted normally to the alcogel layers, and as a result the interlayer pressures were much higher than the pressure at the interface of the alcogel layer edges and the channel sides. This allowed water to flow down the two circumstantial, plane-Poiseuille channels formed by the alcogel layer edges and the sides of the channel.

The substantial increase in pressure drop induced by these alternate flow channels is explained by equation 5.3. An inverse cubic relationship exists between gap height and pressure drop for plane-Poiseuille flow scenarios, meaning the pressure drop will increase cubically as gap height decreases. The alternate flow channels had extremely small gap heights compared to the gap height created by the mesh separator. As a result, drastically different pressure drops were measured for the same flow rates.

$$\Delta P = \frac{Q \cdot L \cdot 12\mu}{W \cdot H^3} \tag{5.3}$$

5.2.2 Posted Perpendicular

The Posted Perpendicular separator was tested next. It was designed with a large gap height, large mesh pore size, and minimal obstructions, in order to produce very low pressure drops (See Appendix A). The Posted Perpendicular separator successfully produced the lowest pressure drop of all separators when tested without alcogel layers on either side. However, the results were extremely different when tested with alcogel layers (See Figure 5.6). The pressure drops measured with alcogel layers were two to three orders of magnitude larger than those measured without alcogel layers. In fact, the maximum pressure drop measured for the alcogel case was 32,300 Pa/m at a flow rate of 8.92 x 10^{-6} m^3/s and the maximum pressure drop measured for the case without alcogel was 455 Pa/m at a flow rate of 3.03 x 10^{-5} m^3/s as seen in Figure 5.6.

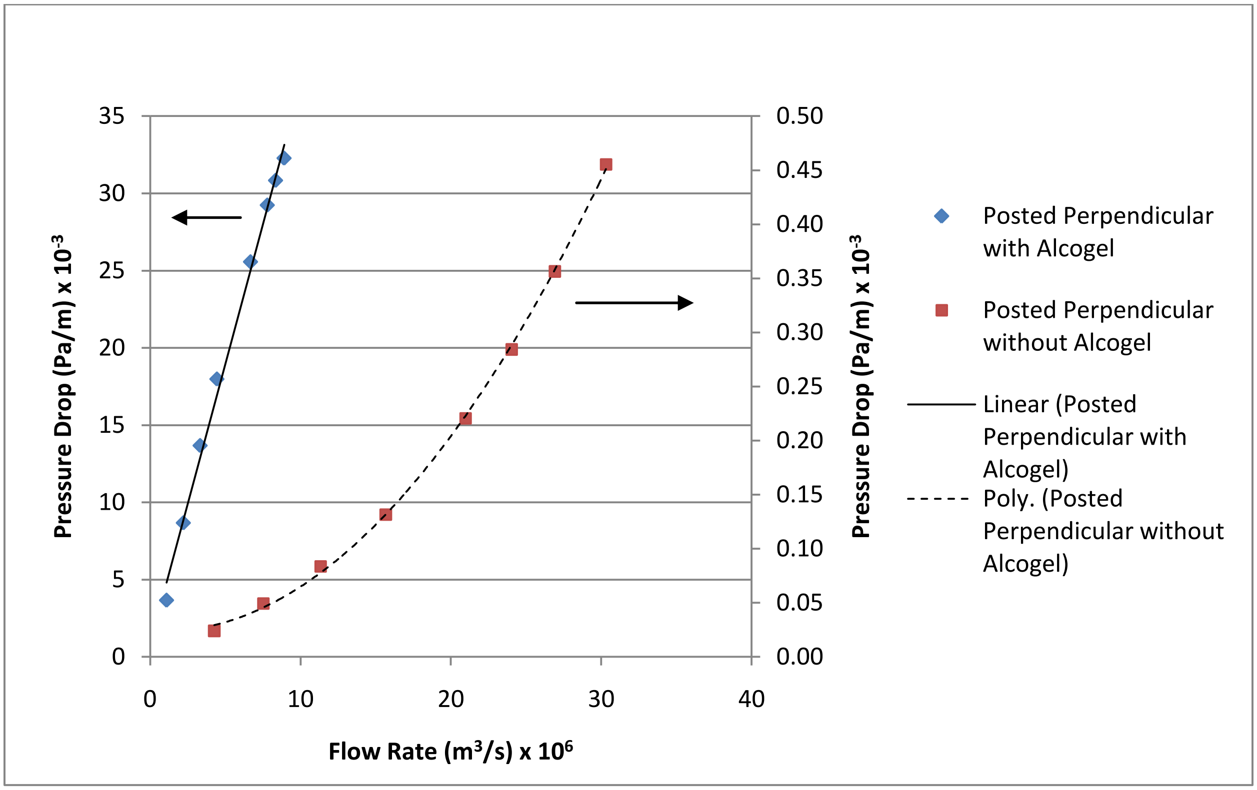


Figure 5.6 Posted Perpendicular with and without Alcogel

In this case, the pore size of the mesh was very large and did little to prevent alcogel from penetrating into the flow channel. As a result, the flow channel was blocked. Little, if any, fluid flowed through the channel created by the separator, and the obstruction to flow caused the pressure drop to increase drastically at relatively low flow rates.

Once again, the pressure drop increased linearly with flow rate and it seemed as if the flow passed through alternate channels formed between the sides of the channel and the alcogel layer edges. There may have been some crevices throughout the layered alcogel/separator system through which the flow crept, but it is likely that most of the fluid flowed down the thin plane-Poiseuille channels created between the chamber sides and alcogel layers. These results and results from the net mesh tests indicated a single mesh separator was unable to maintain uniform flow of aging fluid between alcogel layers.

5.3 Layered Separators with Alcogel

Layered separator configurations were considered next. A layered separator system was thought to provide several advantages over and individual separator including increased flow channel height and resistance to penetration. In order to test this hypothesis, different systems of layered separators were tested with alcogel layers. The layered separator systems included net meshes on both sides of the three separators previously tested in [4], multiple layered net meshes (2 and 3 layers), various fine meshes on either side of a net mesh, and aluminum foil sheets on either side of a net mesh.

5.3.1 Fine Perpendicular, Fine Diagonal, and Coarse Perpendicular Half Strands

The first separator system tested had both the net mesh and an alcogel blanket layered on either side of the Fine Perpendicular separator. If flow through the channel was blocked, one would have seen a linear relationship between flow rate and pressure drop as seen in previous tests of the individual separators with alcogel. However, a quadratic relationship was found between flow rate and pressure drop, indicating the alcogel did not completely block the flow (See Figure 5.7).

Similarly, the Coarse Perpendicular Half Strands separator was tested with both the net mesh and an alcogel blanket layered on its sides (See Figure 5.7). A quadratic relationship was evident for this layered system as well. Finally, the Fine Diagonal separator was tested in a similar fashion. Once again, the quadratic relationship between flow rate and pressure drop was evident (See Figure 5.7). Of the three thicker separators layered with net meshes the fine perpendicular performed best, producing the lowest pressure drops for various flow rates.

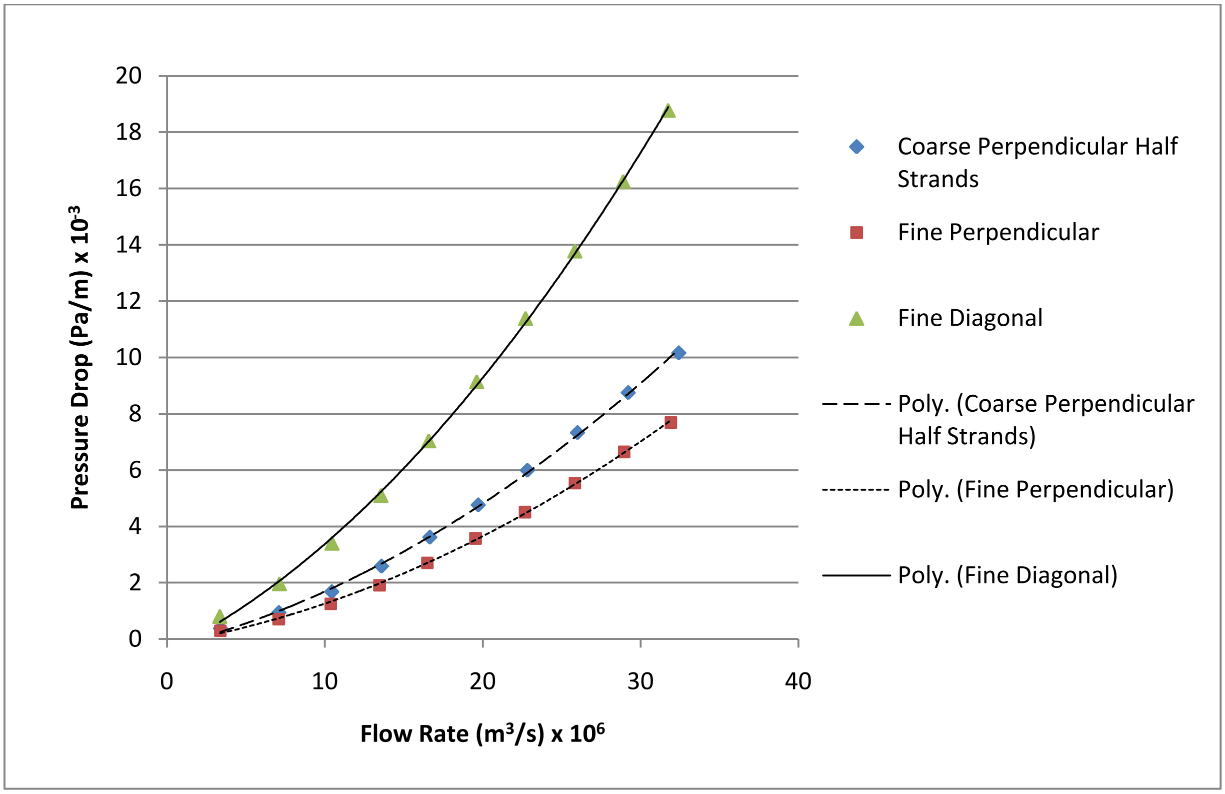


Figure 5.7 Various Separators with Net Meshes

Unfortunately, the Fine Perpendicular, Fine Diagonal, and Coarse Perpendicular Half Strands (See Appendix A) would add considerable height to a separator system and are unfeasible for manufacturing conditions. The overall space occupied by the separator within the roll would increase significantly since the added height of the separator would compound with each roll layer.

The separator height for the Fine Perpendicular layered system would be around 4.1 mm. If the alcogel layers were 5 mm thick the separator would take up about 46% of the aging vessel. If the alcogel layers were 10 mm thick the separator would take up about 29% of the aging vessel. It is impractical for the separator to take up this much space and these thicker layered systems are unrealistic for manufacturing processes as they would drastically reduce overall aerogel blanket production. However, results show a layered system could provide several benefits and should not be ruled out. Therefore, thinner layered options were considered and tested in hopes of capturing the benefits of a layered separator system.

5.3.2 Layered Net Meshes

The net mesh is quite thin, t= 0.95 mm, compared to the Fine Perpendicular, Fine Diagonal, and Coarse Perpendicular Half Strands, t= 2.2 mm, t= 2.2 mm, t= 4.4 mm, respectively. We believed layering several met meshes would not increase the separator height dramatically nor compromise the flexibility of the net mesh. In order to test this hypothesis, two layered separator systems were tested: a two layered and three layered net mesh system (See Figure 5.8).

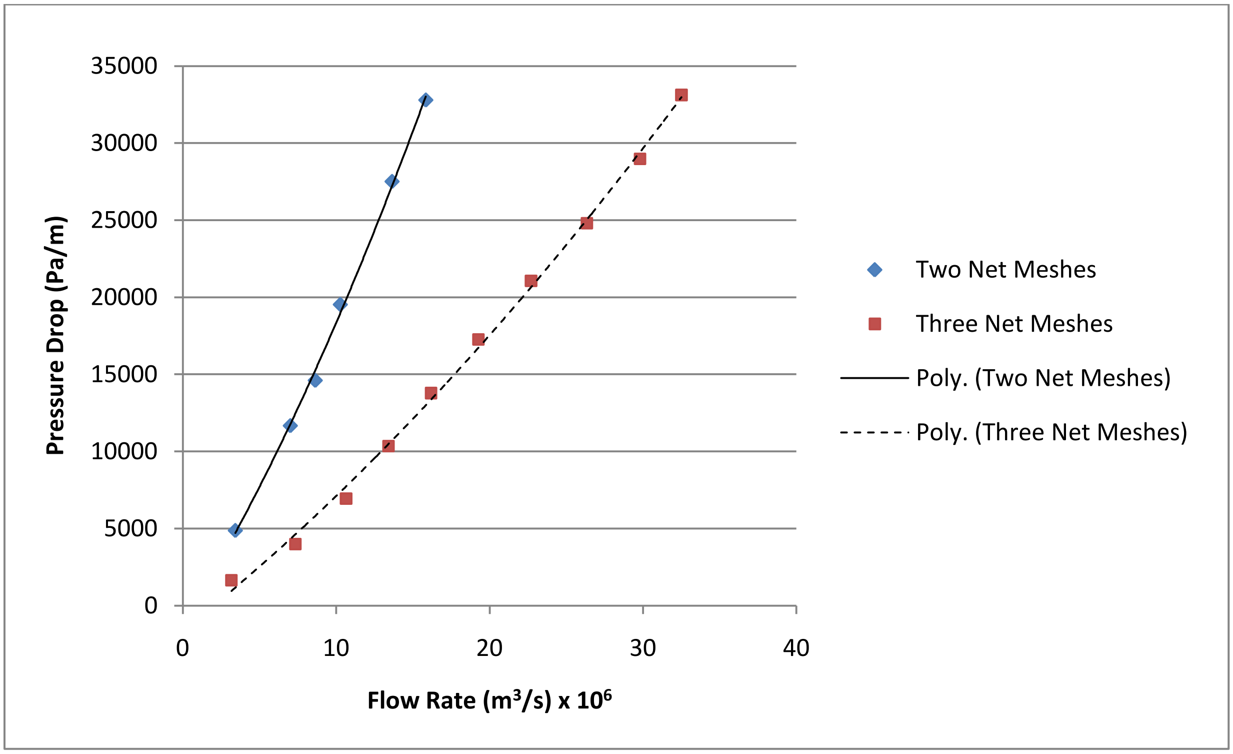


Figure 5.8 Layered Net Meshes

The three layered system outperformed the two layered system, producing lower pressure drops for various flow rates. This was expected since an inverse cubic relationship between separator height and pressure drop exists (See Equation 5.3). The tests of the layered net mesh systems proved that layered thin meshes may prevent alcogel from completely blocking flow. Yet, layering two or three net meshes would double or even triple the separator height. To determine how thin the layered meshes could be, two even finer meshes were layered on either side of a net mesh and tested with alcogel layers.

5.3.3 Very Fine and Semi Fine Meshes Layered with Net Mesh

The finer meshes were chosen with similar geometric relationships between strand size and mesh pore size to those found between the thick separators and the net mesh (See Figure 5.9). For example, the ratio between the net mesh pore area and the Fine Perpendicular pore area is 0.17, and the ratio between the net mesh strand size and the Fine Perpendicular strand size is 0.39. In the scaled system the net mesh was the larger of the two. Therefore, a "Very Fine" mesh was found with a ratio between its pore area and the net mesh pore area of around 0.14, and a ratio between its strand diameter and the net mesh strand diameter of around 0.11 (product number: 9318T51) [20]. The ratios were not exactly the same as the thicker systems (selection was limited to available, commercially made meshes), but they provided similar geometric relationships. The Very Fine mesh was layered on either side of the net mesh and tested with alcogel layers (See Figure 5.10).

The results showed a nearly linear relationship between flow rate and pressure drop. A very slight quadratic behavior was seen, but was negligible. The pressure drop increased quickly at low flow rates suggesting most of the flow was blocked. We believe this was due to the Very Fine mesh's thinness and small pore size. In fact, the very fine mesh felt more like a cloth fabric than a plastic mesh. Without the structural soundness of a thick strand diameter the very fine mesh was unable to prevent the alcogel from penetrating into the flow channel. The alcogel did not penetrate through the mesh pores of the Very Fine mesh, but instead bent the Very Fine mesh into the net mesh pores and blocked the flow as a result.

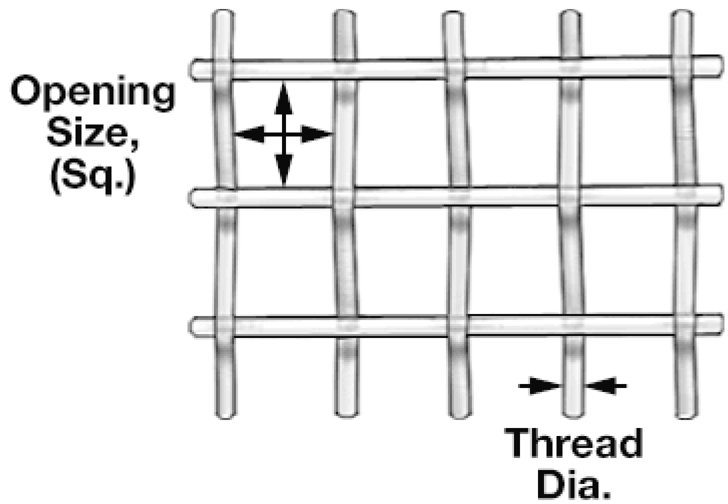


Figure 5.9: Mesh Dimensions [20]

An intermediate "Semi Fine" mesh was found with a larger mesh pore size and strand diameter to determine if a more structurally sound mesh would prevent the alcogel and fine mesh from penetrating into the coarser mesh pores. The ratio of the Semi Fine mesh pore size to the net mesh pore size was 0.48 and the ratio of the Semi Fine strand diameter to the net mesh strand diameter was 0.21 (product number: 9318T21) [20].

The larger strand size of the Semi Fine mesh provided additional structural support and improved performance of the layered system (See Figure 5.10). However, high pressure drops were produced at relatively low flow rates (1.2 x 10^{-5} m^3/s) in comparison to the thicker layered systems tested previously. The Semi Fine layered system was an improvement none the less when compared to an individual net mesh in alcogel, which produced high pressure drops at even lower flow rates (4.0 x 10^{-6} m^3/s as shown in Figure 5.5).

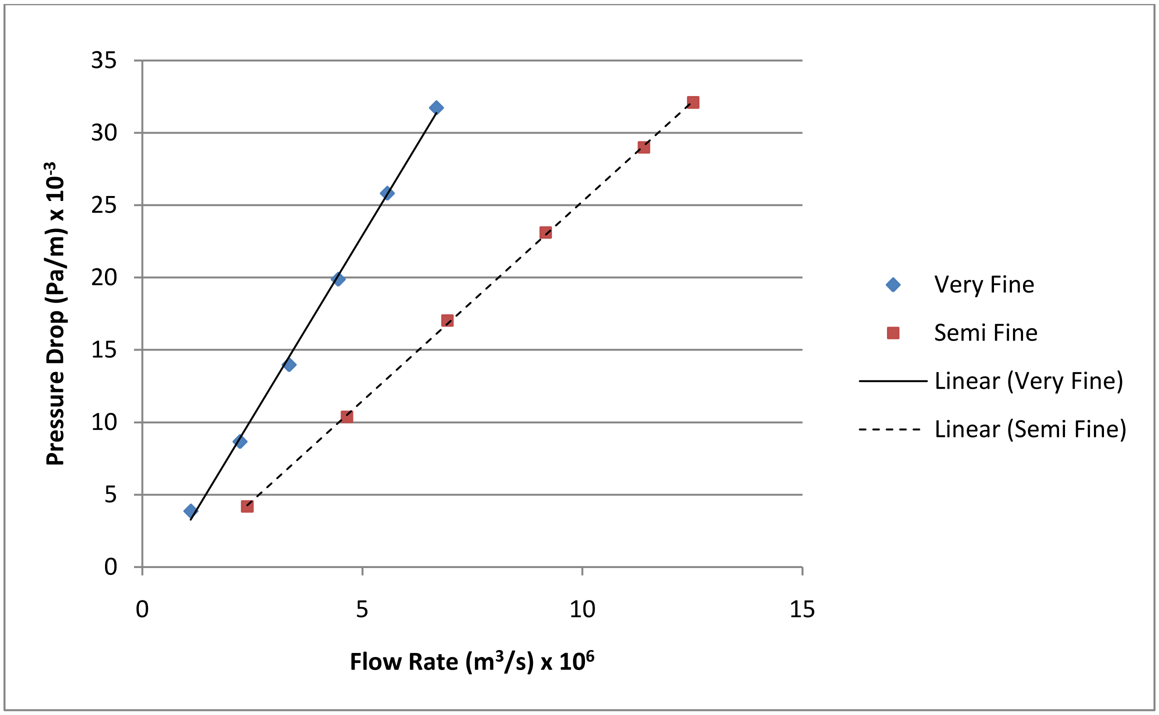


Figure 5.10 Net Mesh Layered with Finer Meshes

5.3.4 Aluminum Foil with Net Mesh

As discussed in Chapter III, increasing temperature uniformly throughout the alcogel roll blanket during manufacturing would decrease aging time and improve aerogel blanket quality. There may be ways, other than just layering separators, to increase roll temperature, such as layering a separator with higher thermal conductivity on either side of a mesh separator.

The thermal conductivity of a plastic, in this case the polypropylene net mesh, is much lower (0.12 W/m·K) than that of aluminum (237 W/m·K) [3]. Layering aluminum foil, which is approximately as thick as the Semi Fine mesh (See Table 4.2), on either side of a net mesh would provide several benefits. The layered system would prevent the alcogel from penetrating into the flow channel and completely blocking flow. Additionally, the aluminum would heat up and increase the inner roll temperature where flow blockage occurred. The interlayer roll temperature may heat up at a slower rate, but aging time would decrease nonetheless. This hypothesis was not tested, but pressure drop test were run to determine if the aluminum would maintain uniform flow between alcogel layers.

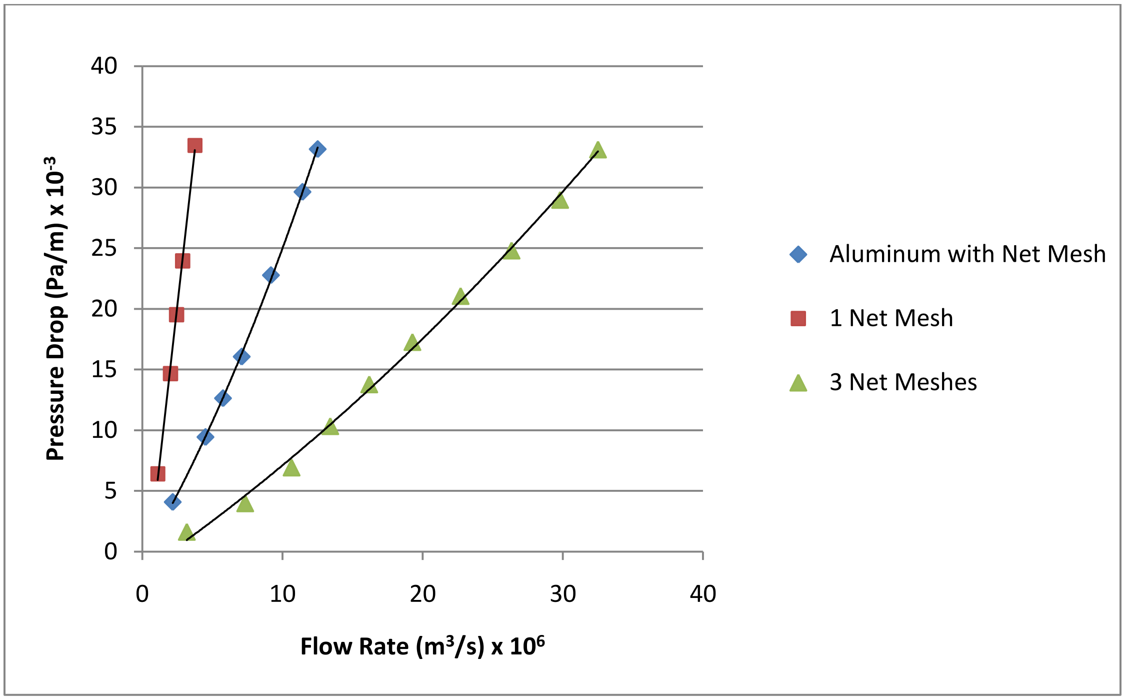


Figure 5.11 Aluminum Foil with Net Mesh Compared to One and Three Layered Net Meshes

The aluminum with a net mesh produced lower pressure drops than a single net mesh (See Figure 5.11). Despite the slight improvement, high pressure drops were induced at low flow rates. The transducer maxed out around 12 x 10^{-6} m^3/s. In terms of pressure drop the three layered net meshes definitely outperform aluminum layered with a net mesh. At this point it appears that layering several net meshes would be the ideal solution for maintaining uniform flow of aging fluid. However, the pros and cons of each separator system must be thoroughly considered when choosing the optimal separator system.

5.4 Summary of Results

The layered separator systems outperformed the single separators in all tests producing lower pressure drops for various flow rates (See Figure 5.12). The layered system consisting of the Fine Perpendicular with net meshes produced the lowest pressure drops, while a single net mesh produced the highest pressure drops. The Semi Fine mesh layered with a net mesh and the net mesh layered with aluminum foil produced very similar pressure drops for various flow rates performing slightly better than a single net mesh. However, they produced high pressure drops at relatively low flow rates and maxed out the transducer around flow rates of 12 x 10^{-6} m^3/s.

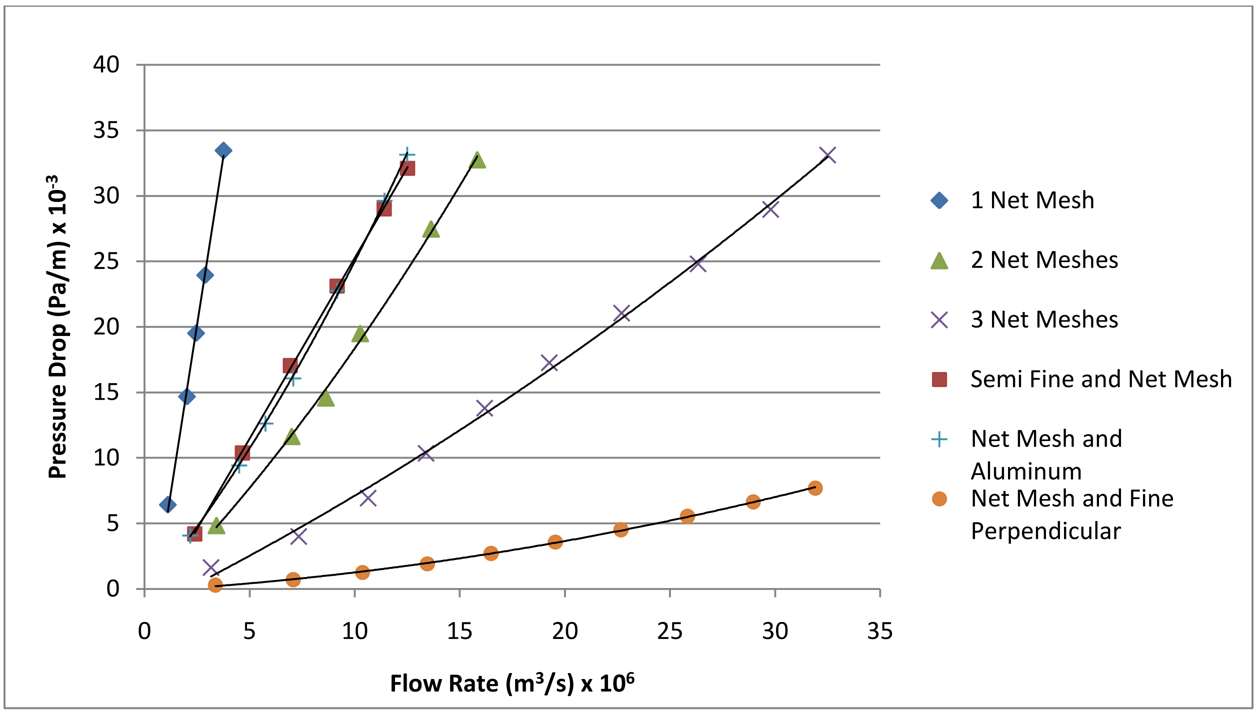


Figure 5.12 Comparison of Various Layered and Single Separator Systems

The two layered net meshes performed slightly better than the Semi Fine and aluminum layered systems. However, the two meshes doubled the separator height. One must decide if the benefits of slightly improved performance would outweigh the loss of aerogel blanket production caused by the increased separator height. The three layered net meshes produced even lower pressure drops and maxed out the transducer around much higher flow rates of about 32 x 10^{-6} m^3/s. The three net meshes performed second best to the Fine Perpendicular layered system. Table 5.1 displays the flow rate at which the maximum pressure drop was measured for each separator system.

	Mesh Separator	**Maximum Measured Pressure Drop (kPa/m)**	**Flow Rate (m^3/s) x 10-6**
Single	Net Mesh	33.5	3.8
	Posted Perpendicular	32.3	8.9
Layered	Fine Perpendicular With Net Meshes	7.7	31.9
	Fine Diagonal with Net Meshes	18.8	31.8
	Coarse Perpendicular Half Strands with Net Mesh	10.2	32.4
	Net Mesh with Very Fine Meshes	31.7	6.7
	Net Mesh with Semi Fine Meshes	32.1	12.5
	Two Net Meshes	32.8	15.8
	Three Net Meshes	33.1	32.5
	Net Mesh with Aluminum	33.2	12.5

Table 5.1 Maximum Measured Pressure Gradient for All Separator Systems

Analysis of results reveals that both the three layered net meshes and the aluminum layered system show promising results. Both would provide simple solutions and would require slight adjustments to manufacturing practices already in use. If full scale tests indicate that either option successfully decreases aging time, a simple solution has been found for a complicated problem. The exciting discoveries made in this work have the potential to conserve significant amounts of energy and money by reducing aging time during the manufacturing of aerogel insulation blankets.

Chapter VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The Fine Perpendicular layered system produced the lowest pressure drops of all layered systems tested. However, the Fine Perpendicular layered system increased the separator height more than six fold. The added height would multiply with each roll layer and occupy anywhere from 29% to 45% more space per roll. The Fine Perpendicular separator was also quite brittle and inflexible, and would not be conducive for rolling. It is essentially unfeasible for actual manufacturing processes.

Thinner and finer meshes with thicknesses ranging from 0.08 mm to 0.015 mm were found to create a layered system with minimal increase in separator height. The Semi Fine layered system produced lower pressure drops than a single net mesh, but maxed out the transducer at relatively low flow rates. The aluminum layered system performed almost identically to the Semi Fine layered system, and also maxed out at relatively low flow rates. Although these two systems outperform a single net mesh, the slight improvement in performance may not be sufficient for maintaining uniform flow between alcogel roll layers. Nonetheless, the heat transfer characteristics of the aluminum layered system should be considered before ruling it out as a viable solution since the high thermal conductivity of aluminum may be enough to increase inner roll temperatures in areas where the aging fluid does not flow.

The two net meshes performed even better than the Semi Fine and aluminum layered systems. That being said, the two net meshes may not enhance flow in all roll locations, unless very high pressure drops are induced across the flow channels created by the alcogel roll layers. Additionally, this separator system would not have the benefits of a high thermal conductivity and the two net meshes would produce a separator height about 50% greater than the aluminum and Semi Fine layered systems. Aging time and blanket quality would improve slightly when using two net meshes, but less aerogel blanket would be produced. The slight increase in performance may not compensate for the added separator height. A layered separator system that produces even lower pressure drops for various flow rates should be considered.

The three net mesh layered system produced the second lowest pressure drops of all the systems tested. Layering three meshes would triple the separator height, but would provide several other benefits. Flexibility of the net mesh would not be compromised by layering the meshes, and the three layers create a thicker channel through which aging fluid may flow. More of the aging vessel would be occupied by the separator, but it may be less than expected. The alcogel blanket has a very low modulus of elasticity and the high interlayer pressures may cause the alcogel blanket to penetrate into the two outer meshes. Only the inner net mesh would account for the increase in separator height and the overall height would not triple. A full scale alcogel blanket should be rolled with three net meshes to determine the actual amount of space that would be occupied by a three layered net mesh system.

Additionally, a three layered net mesh system would be easy to implement in manufacturing processes. Industry currently rolls a single net mesh with the alcogel blankets.

Adding two layers to the mesh currently in use would not introduce new materials to the process and would require manufacturing techniques already in place. However, full scale tests should be conducted to expose any complications that may arise from a layered system.

Consideration of all factors and limitations for the best separator system design indicates two layered systems as viable solutions. The aluminum layered system showed moderate improvement when compared to a single net mesh producing lower pressure drops for various flow rates and may improve heat transfer in areas that remain unexposed to heated aging fluid. Of the layered systems with tolerable height increases, the three layered net mesh system produced the lowest pressure drops. If adequate pressure drops are induced across the roll channels created by the separator, the three layered net mesh would maintain uniform flow between the alcogel layers. Both the aluminum layered system and the three layered net mesh system should be thoroughly considered before choosing the best design.

Based on these findings, it is recommended that both the aluminum layered system and three layered net mesh system be tested at full scale. The mechanics of rolling three net meshes may be much simpler than layering aluminum foil on either side of a net mesh, and, likewise, layering the aluminum with the net mesh may prove simplest. Full scale tests would determine the optimal separator design for implementation in actual manufacturing conditions.

It is also important to determine the decrease in aerogel blanket production caused by the increase in separator height. The benefits of the three layered system may be nullified if the three layered net mesh system significantly decreases the amount of aerogel blanket produced per roll. By manufacturing a full size roll one could determine the decrease in aerogel production incurred by each separator system. Analysis of these full scale tests would determine the optimal separator system for maintaining uniform flow between alcogel roll layers, which would uniformly increase inner roll temperatures and reduce aging time.

6.2 Recommendations

Future work should improve upon the experiments completed in this research. Several adjustments and improvements could be made to the experimental set-up to produce more accurate and informative results as discussed later in this section. Additionally, different separator systems should be considered to address the varying interlayer pressures in spiral wound alcogel rolls. This section gives several recommendations for future experiments and alternative separator systems.

All pressure drop tests were run using a high precision positive displacement gear pump. Pump cavitations occurred a little above flow rates of 30×10^{-6} m^3/s. Due to the pumps limitations no data was obtained for flow rates above 30×10^{-6} m^3/s. It is advisable to get a pump capable of pumping higher flow rates without cavitations for future experiments.

Achieving higher flow rates is especially important for validating the experimental set up. The open channel, or plane-Poiseuille, case produced extremely low pressure drops at relatively high flow rates. For example, the plane-Poiseuille case produced a pressure gradient just over 450 Pa/m for a flow rate of 30×10^{-6} m^3/s, whereas the three layered net mesh system produced a pressure gradient around 29,000 Pa/m for a flow rate of 30×10^{-6} m^3/s. The pressure gradient produced by the three layered net mesh system is several orders of magnitude greater than that produced by the open channel case. It would be beneficial to see how the experimental set up behaves for the open channel case at pressure gradients closer to those seen in the layered and single separator flow tests. Therefore, in future experiments, a pump capable of producing higher flow rates should be used to validate the experimental set-up.

Additionally, if pressure drop tests were to be redone or new tests were to be completed, a few changes could be made to improve accuracy and depth of information retrieved. The pressures applied to either side of the aerogel blanket clamped within the flow channel were unknown. The pressures were high enough to imbed the alcogel into single meshes and reproduce general manufacturing conditions, but the exact pressure applied to the test system was not known. The lab set up gave a general representation of actual manufacturing conditions, but did not portray results for known interlayer pressures. Essentially, it was not know whether the situation produced in the lab represented interlayer pressures close to the center of the roll or near the outer radius of the roll.

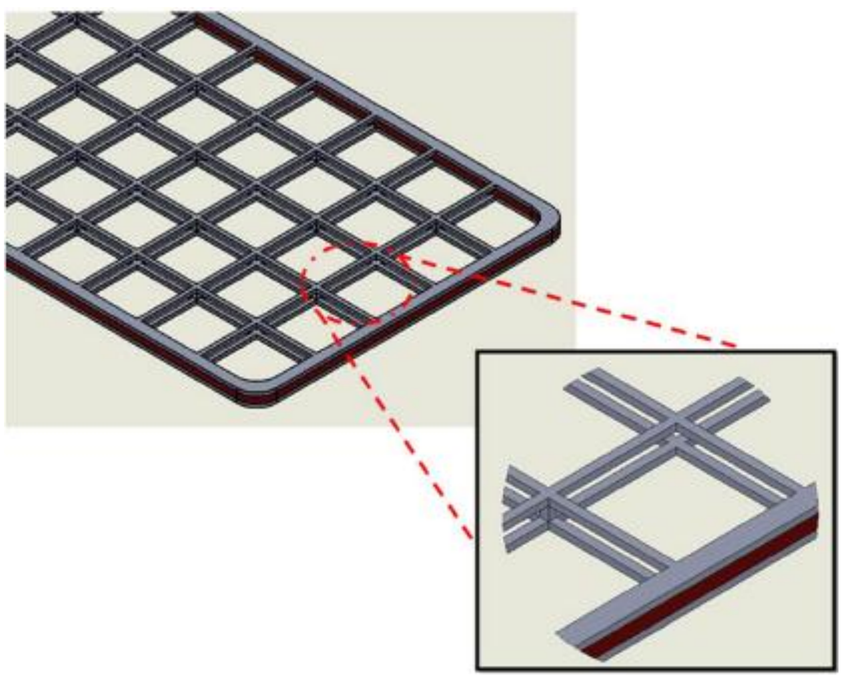
Results from tests conducted under more controlled conditions may reveal that pressure drop tests behave differently for a range of interlayer roll pressures. If future test are run, it would be advantageous to develop an experimental set up capable of measuring the force applied to the layered system within the flow channel. This may be achieved using the methods discussed in Section 4.3.2.

Future experiments should also consider other creative design ideas for the separator system. For instance, a separator of varying thickness may provide several benefits over a separator with uniform thickness. Interlayer pressure models created in [11] displayed higher interlayer pressures near the center of a wound roll. The model also showed the interlayer pressures decreasing as the distance from the center of the roll increased. Therefore, a separator with varying thickness may be more efficient than a separator of uniform height. The separator height would be thick near the center of the roll and steadily decrease. Future experiments could determine the level of the varying thicknesses throughout the spacer to obtain the ideal configuration.

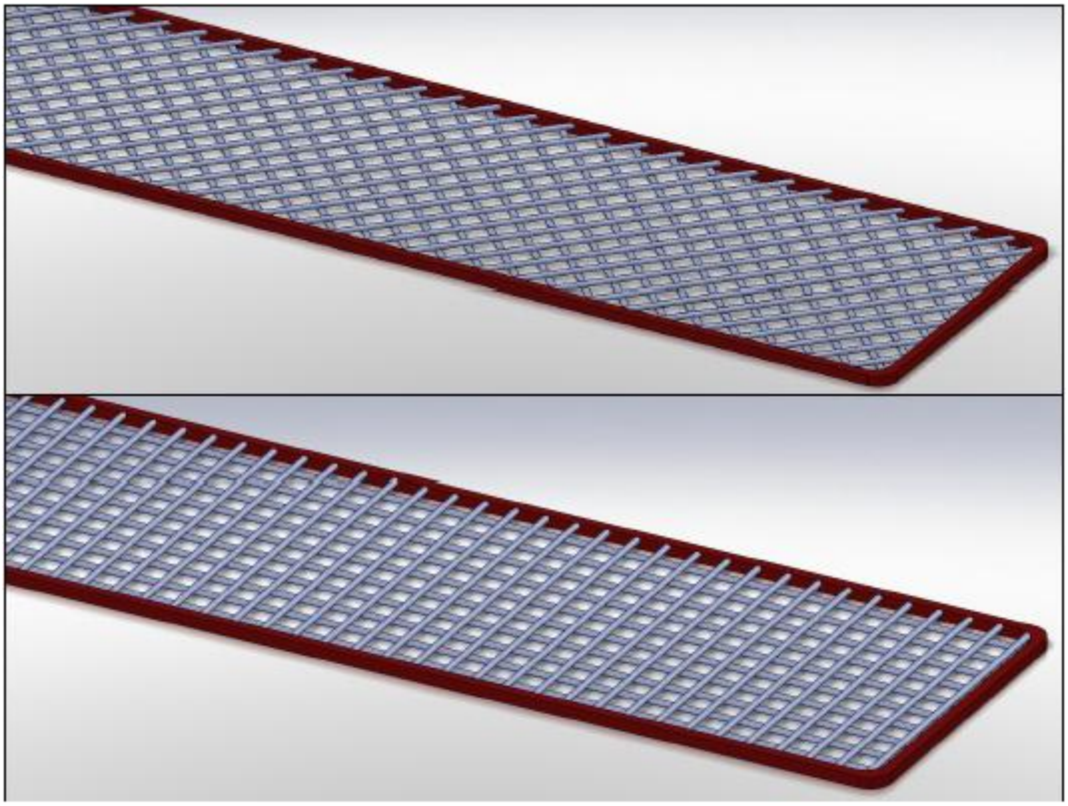
APPENDICES

APPENDIX A

Separators

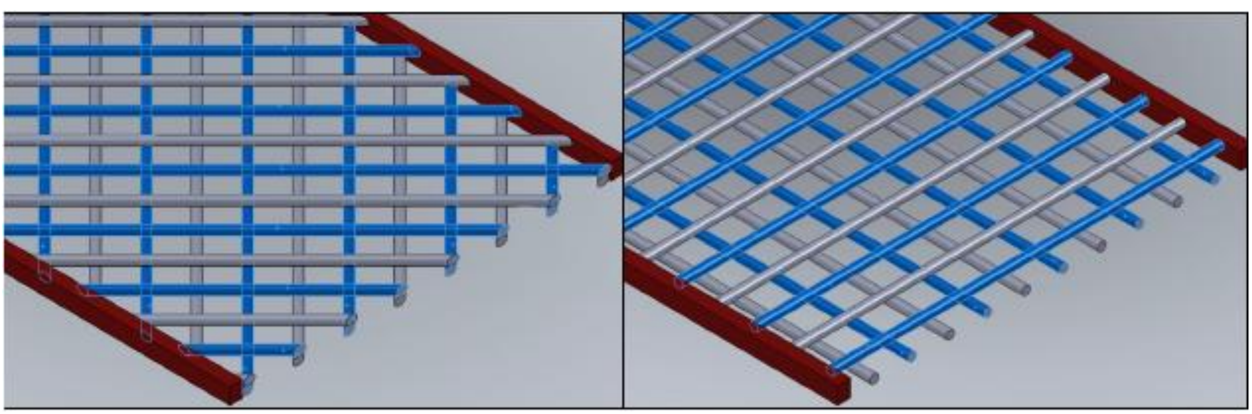


Posted Perpendicular



Top: Fine Diagonal

Bottom: Fine Perpendicular



Left: Coarse Diagonal Half Strands

Right: Coarse Perpendicular Half Strands

(Highlighted strands are removed to create the "Half Strands" separators)

APPENDIX B

Experimental Procedure for Pressure Drop Tests

Setting up Hardware

1) Ensure you have all necessary parts
    a. Flow Chamber (Including Four outlet tubes to water recirculation tank)
    b. Gear Pump (including 1 inlet tube and 2 out let tubes attached, power cord)
    c. Water recirculation tank
    d. Differential Pressure Transducer (Inlet and outlet tube attached, power and USB cords)
    e. Data Acquisition Station: LabVIEW program installed, transformer (120V to 24V DC), NI interface (NI_cDAQ9174,NI_9203)
2) Create closed loop between the flow chamber, gear pump, pressure transducer, and water recirculation tank.
    a. Flow chamber has 3 inlet lines- the central line is connected to the high pressure side of the pressure transducer; the remaining 2 are connected to the outlet of the gear pump.
    b. Flow chamber has 5 outlet lines- the central line is connected to the low pressure side of the pressure transducer; the extra 4 lines are led to the recirculation tank.
    c. Gear pump- Two outlet lines run to inlets of flow chamber; inlet line runs from recirculation tank.

d. Pressure Transducer has two lines- one line to each central plug of the flow chamber

e. Water recirculation tank- Holds the four outlet lines of the flow chamber and the inlet line of the gear pump. Fill recirculation tank with water.

f. DAQ Station- Ensure wired correctly (see installation guide for Setra 230)

3) Connect all power and USB cords (from pressure transducer to computer etc).

   a. Look for the "ready" light to be lit on the NI_cDAQ9174 (this signals the DAQ station recognizes the transducer and is ready to go)

Setting up Software

1) Open LabVIEW program (VGIFScadaV2.vi and Pump_Calibration_Program.vi)
2) Verify the LabVIEW (VGIFScadaV2.vi) program is running correctly
   a. Start Gear Pump and LabVIEW program
   b. Look to see a pressure drop increase for increased flow rates.
3) Once the program is up and running you can begin calibration for the cartridge/interlayer set up you choose

Pump Calibration

Each separator needs to be calibrated before testing.

(VGIFScadaV2.vi does not need to be running during calibration)

1) Open pump calibration program.
2) Bleed any air bubbles out of system by pumping water through flow channel at varied flow rates.

3) Turn off pump to begin actual calibration.

4) While the pump is stopped, set the flow rate to around 400 rpm. Switch to time mode on Pump and set to 60 seconds.

5) Start pump while in “time” mode and switch flow chamber outlet lines to a beaker (The switch of lines needs to coincide with the start of the pump; the more precise the switch the better since this is a calibration)

6) The pump will stop after 60 seconds. Remove the lines from the beaker.

7) Record the amount of water accumulated in beaker.

8) Repeat the above procedure for a total of five calibration points ranging from 400 to 3000 rpm

   a. Be sure to bleed out air bubbles at all flow rates (esp. higher flow rates)

   b. Be sure to record and save all data for each flow rate

9) Input RPM values and measured flow rate values into the pump calibration program

10) Run the program for different rpm values of interest to determine the calibrated flow rate. Use this calibrated flow rate as the “pump flow rate” value in the VGIFScadaV2.vi program.

Testing the Separator

Once the pump is calibrated for the separator use the following test procedure:

1) Ensure the VGIFScadaV2.vi program is open.

2) Ensure all air bubbles are bled out of the flow system and pressure transducer lines (NO AIR BUBBLES!).

3) Start the test with no flow rate.

4) Start the VGIFScadaV2.vi program.

    a. You should see some pressure difference; this value becomes the zero pressure offset and should be entered into the appropriate box on the user interface.

    b. Once the zero pressure offset is entered, the pressure difference should read around zero for no flow rate.

5) Initiate the pump at a low flow rate (200-300 RPM)

    a. Calculate the calibrated flow rate for the chosen RPM using the pump calibration program and enter the calibrated value into the VGIFScadaV2.vi program where it says "Pump Flow Rate."

6) Allow the pressure difference to stabilize and let it run for 30-45 seconds.

7) Increase the flow rate incrementally to 3000 RPM.

    a. After each increase enter the calibrated flow rate for the appropriate rpm value into the VGIFScadaV2.vi program. This ensures the written txt file shows the correct flow rate for each pressure difference measurement.

8) The program and be stopped after 3000 RPM and the pump turned off. If this is the last test the power supply may be shut off.

9) A txt file has been written to a designated folder (embedded in the LabVIEW code) and can be retrieved for analysis.

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