

Title: The Role of Orifice in Hydroentanglement

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ABSTRACT:

Hydroentanglement is a process of entangling a web of loose fibers on a porous belt or moving perforated or patterned screen (wire screen or perforated drum) to form a sheet structure by subjecting the fibers to multiple rows of fine pressure jets of water. It is an energy transfer process that changes and strengthens the array of loose fibers, imparting the desired physical, tactile and aesthetic properties. Over the last decade, the pressures have been increased from less than a 1000-PSI to today's high pressures reaching 4000 PSI or more. The shape of the orifice however, has essentially remained unchanged. The higher pressures may result in a totally different behavior and the flow may become unstable and drops may be formed instead of a columnar flow. The higher pressures also result in much faster deterioration of the jet strips. It is the former however, that forms the topic of this research.

INTRODUCTION

Background:

Spunlacing, hydroentanglement, hydraulic needling and water-jet entangling are all terms that describe a versatile process for manufacturing nonwoven fabrics using fine, closely spaced, high-velocity jets of water to rearrange and entangle loose fibers. Water jet entangled fabrics consist of mechanically interlocked fibers and fiber bundles where the energy that causes the fibers to interlock is supplied by high-pressure streams of columnated water. In the entanglement operation, water jetted downwards through the holes of the injectors perforates the fiber web and then is returned upwards by the conveyor belt fabric supporting the web. It is said that this combination of both direct and re-directed water jet creates a vigorous agitation within the web itself. It is this action, which achieves the efficient entangling of the fibers, producing nonwovens, which are absorbent, drapable, lint-free and strong without the need for a binder. These textures include lace effects, which have given rise to the term "Spunlacing". [1], [2]

The hydroentanglement process has been in commercial use since the early 1970s by companies such as Dupont and Chicopee. From 1963 onto the 1970s, Dupont established five patents that were to become the core of the hydroentanglement. Releasing these patents led to further developments in the hydroentanglement field, especially in Japan. One notable group was

Asahi Chemical Industry. Other companies have since developed their own entanglement systems. [3]

The growing interest in this technique has convinced some machinery builders to manufacture industrial equipment based on this technology. Honeycomb Systems in the United States and Perfojet in France and Fleissner in Germany are among the best-known equipment manufacturers. [4]

Over the years, the technical improvements have resulted in lower, acceptable values of capital investment, reduced energy consumption, and lower operating and maintenance costs. All these improvements, combined with better utilization of proper fiber composition and trouble-free, computer-controlled operation, assure consistent end-product properties and improve process economics. When we look at the today's industry, currently 110 spunlace plants are in production worldwide and additional lines are scheduled to start up around the world. It is estimated that approx. 12% of nonwovens produced in the world are made through a hydroentanglement product. [5], [6]

Various steps are of importance in the hydroentanglement process. While some of them are typical in a nonwoven process, some of them are unique to the process of hydroentanglement. The steps characteristic for producing spunlaced nonwoven fabrics include: [1]

- Fiber Selection
- Fiber Preparation and Web Forming
- Hydroentanglement Process
 - Supporting Substrate
 - The Entangling Unit
 - Water extraction
 - Water Circulation and Filtration
 - Drying
- Winding
- Finishing (optional)

While all the steps listed above do have an importance in hydroentanglement process, this research focuses on the entangling unit.

Entangling Unit:

In the entangling unit, fibers in web are subjected to fine, high-pressure jets of water. These jets are usually arranged in multiple rows and are directed at the fibrous web that is supported and carried by a moving screen. As these fibers pass under the high-pressure water jets, they entangle and form a sheet structure. [3]

Whatever the support system is (belts or drums), the key elements of the entanglement operation remain water needling and the water re-circulation system. Water needling transfers energy from the high-pressure water in the injectors to the web. Within the entanglement zone, the hydrodynamic forces act to move and rearrange the fibers, intertwining the fibers and making them conform to the shape and pattern of the entangling substrate. [1]

The pressure applied to a precursor web depends only on the type of fibers and forming equipment and on the basis weight of the web. Generally, the water pressure is increased stepwise

from the first to the last injectors. That is because the fibers in the fiber web are bound to each other to an extent such as to enable the fibrous web to withstand the following entangling process at a high pressure so as to prevent fibers being flushed away or the fibrous web disintegrating.

Under normal conditions, the first manifold operates at low pressures (approx. 700 PSI) while the other manifolds operate at higher pressures (4000 PSI or more) the number and the dimensions of the water-needles produced by the manifolds are adjusted to the type of web being entangled. Generally, the first manifolds deliver relatively coarse needles (120 microns) to achieve the best entanglement while the last manifolds produce finer needles (80-100 microns) to give a final product with a smooth surface. [7]

Hydroentanglement is basically an energy transfer method where the system provides high energy to water jets and then transfers the energy to the precursor web. In other words, the energy is delivered to the web by the water needles produced by the injector. The amount of energy delivered in the web is a crucial parameter influencing the fabric structure and properties since it affects fiber entanglement completeness. Varying the amount of water-jet energy delivered to the web controls the amount of entanglement. There is a precise balance between the energy/process considerations and the desired end property requirements. As a result, the amount of entanglement is proportional to the energy treatment and is reflected in the tensile strength, surface integrity, elongation and initial modules of the fabric. Most of the tensile strength is developed early during entanglement treatment, while surface integrity and the initial modules are established as the function of the final step. Surface integrity also depends on the energy distribution between the two sides of the web. The tensile strength of the fiber increases to a certain point as the water pressure increases (due to high energy from water imparted to the fiber entanglement). Web strength is derived from physical entanglement and the resultant inter-fiber friction. [4]

In hydroentanglement technology, the energy application parameter of horsepower-hours per pound of fiber (hp-hr/lb), or alternatively kilowatt-hours per pound (KW-hr/lb) is used to define the energy applied. With this classification, three levels of energy application are chosen depending on the water pressure required for partial or complete entanglement of the web: High-energy systems, medium energy systems, low energy systems. Today, most hydroentanglement systems belong to the high-energy category because they are flexible enough to entangle a wide range of products having different basis weights, various fiber compositions, and different physical properties. Higher water pressure means fewer injectors are used, requiring less water and a lower capital investment. [1], [5]

The amount of energy carried in a jet is a function of its velocity and velocity is in turn a function of pressure. Since energy intensity is proportional to the 1.5 exponent of the pressure, a change in pressure levels has a significant effect on the degree of entanglement. [8]

Calculations per applied energy also include the jet size, the number of the jets per unit length and the quantity of fiber or fabric processed. In reality, entanglement is highly complex process of interacting and interrelated variables that can reduce down in a general sense to how material behaves under different levels of applied energy. This is one of the reasons why hydroentanglement holds so much promise- there are so many variables to manipulate, so many degrees of freedom for innovation to create new products. [8]

The quality of entanglement depends on the energy input imparted to the sheet (number of manifolds which are being used, water-pressure in these manifolds, number and dimensions of the water-needles produced by these manifolds) and also the type of fibers forming the web.

Orifices:

The heart of the entanglement systems is a successive bank of jet manifolds. Since the energy is delivered to the web by the water needles produced by the injector, the orifice characteristics play a critical role in the process. The manifold design needs to insure uniform pressure distribution across the width as well as allow for rapid jet strip removal without shutting down the line. The manifold mounting should allow for a sufficient number of manifolds necessary to achieve product performance at high speeds. As a general rule, the behavior of the water jet is dependent upon the orifice from where the liquid is applied against the fiber web.

The orifice holes are usually .005" - .007" in diameter, are spaced at a density of 30-60 holes per inch. The jet diameter and jet spacing are selected to maximize the energy flow and impart specific qualities to the web. [1]

In hydroentanglement, it is important that the individual liquid streams do not cause streaking or non-uniform fiber entanglement across the layer of fibrous material. The water jet has to cause entanglement rather than rearrangement of the fibers. It has to be substantially non-diverging and uniform in width throughout its length under a pressure to effect fiber entanglement, which results in uniform fiber entanglement.

Generally the width of the water jets curtain is dependent upon the width of the slot from where the liquid is applied against the fiber web. Since the slot has to have "uniform width" that means not only that the slot width at any point along its length is substantially constant, but more generally that a selected slot width can be maintained upon operation of the device, so that one portion of the slot does not intentionally vary in width from other portions of the slot.

The profile of the slot from where the water jets curtain is delivered may vary. The profile may be square, rectangle, cylindrical and etc. One or both of surfaces defining the slot profile may be serrated so that the serrated curtains are obtained. The water jets curtain delivered through the slot may be flat backed, square wave or a constant width curtain described by a square wave function.

To produce a uniform water jets curtain, several factors are important. These are:

- The liquid must be contained in the chamber of the device selected under a pressure sufficient to affect the desired degree of fiber entanglement for the linear speed of the backing screen and web. The liquid pressure may be up to about 5000 psi or higher, when the speed of the web past the water jets curtain is high. However, the liquid pressure is preferably about 500-2000 psi. If the pressure varies the width of the water jets curtain does not change since the width of the slot does not vary but the energy being applied to the web may vary resulting in uneven degree of entanglement across the fiber web.
- The width of the water jets curtain will be determined primarily by the width of the slot from which it is delivered.
- Generally the water is perpendicular to the fabric. If the angle changes, the tensile strength changes. The divergence of the jet curtain may affect the efficiency of the process. It should be no more than 5°. The curtain is preferred to have a divergence as close to 0° as possible and no greater than 3°. It has been found that a divergence of 4° is satisfactory when

the water jets curtain is delivered from a slot of 0.005" width, under a pressure of 200 psi at a distance of 3/4" from the web. The web may be positioned about 1/2" to 1 1/2" below the orifices. The spacing of the device from the fiber web will depend upon the fabric character desired but in general, the device should be as close as mechanically possible to the web. It may be from about 1/4" to 3/4".

- And also it is important that the machined surfaces are rigid, essentially independent of the high pressure under which water jets curtain is being delivered, so that the width of the slot and water jets curtain being delivered remains unaffected. [9]

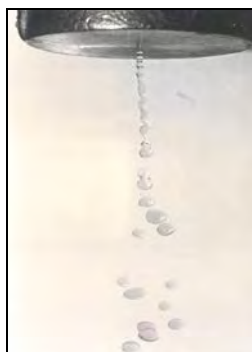
Droplet Formation:

Droplet formation must be considered in two parts, the formation at the surface of orifices and formation from jets. There are four distinctive regimes of drop formation, dependent in a general way, on the injection velocity of the dispersed phase: [10]



Orifice surface regime: The most commonly investigated region is the orifice surface regime. This mode of droplet formation is dominated at *low injection velocities*, and is characterized by the absence of any dispersed phase at a level above the orifice surface in excess of that being incorporated into the drop. [10]

Vibrating jet regime: At *higher injection rates*, the site of the droplet formation moves away from the surface and occurs at the top of a jet, of dispersed phase. This is the vibrating jet regime and is characterized by a wave-like constriction and expansion of the jet, before the drops break off. This variation in jet diameter is symmetric to an axis through the center of the jet and orifice. [10]



Thrashing jet regime At *higher velocities* the disturbance of the jet is no longer axisymmetric, but becomes serpentine in character. This is the thrashing jet regime.[10]

Atomization regime: When subjected to *very high injection rates*, the jet straightens and very small drops are formed by being peeled off the jet surface. This is the atomization regime. [10]



The regime of flow for a given situation has a profound influence on the droplet size. To be able to understand the droplet formation, specific surface and two characteristics of jet lengths (vibrating and thrashing jet regions) must be examined to determine the correlation between specific surface and breakup length; for various orifice types, liquid properties and injection rates.

With increasing distance from the orifice, the jet necking or reduction in the diameter of the liquid jet starts. This is quite common in both vibrating and thrashing jet regions; most particularly when large diameter ($1/4$ " or larger) orifices are used. It is observed that all orifices with a diameter greater than $1/16$ " exhibited a reduction of the jet diameter with increasing distance from the orifice surface. The jet constricts rapidly near the orifice, and attains a nearly constant diameter at greater distances. This constriction is caused by the acceleration of the jet liquid under the influence of buoyant forces. For a given orifice and system, jet constriction decreases with increasing flow rate (Weber number). This shows that inertial forces must be considered in any model of jet diameter reduction.

An important factor of jet mechanics is the length that the jet attains before breakup. Breakup length is the distance from the orifice surface to the tip of the last segment of the dispersed phase, which is connected to the jet.

In order to predict the droplet formation, it is necessary to know what the actual diameter of the jet is at a point near droplet formation. This diameter is in turn a function of the distance from the orifice to the site of droplet formation.

The hydroentanglement efficiency is a function of the shape as well as the mass transfer in the system. Drop size and droplet coalescence were found to have pronounced effect on mass transfer coefficients. Interfacial tension is perhaps the most important characteristic of an interface, and represents the work required to expand the interface by a unit area.

One of the most frequently cited causes of anomalies in drop velocity and mass transfer studies is the deformation of the drop from a spherical shape. Besides, internal circulation has been found to cause considerable changes in the fluid dynamics, and mass transfer behavior of drops.

Drop size has been found to be affected by the droplet coalescence and breakup in the column, after their initial formation. The events leading to the coalescence of a drop at an interface is shown to be non-instantaneous, and an unbelievably complex phenomenon. Another determining factor for the average drop size is the breakup of drops in the column after they have

been formed. It has been pointed out that the maximum stable drop size cannot be generalized, but is a function of flow conditions.

Lord Rayleigh, in a series of pioneering works, found that the surface of a fully developed jet takes on a wavelike appearance at points removed from the orifice. When a vertical jet is formed, the fluid in this jet undergoes acceleration under gravity. As the jet accelerates, the cross sectional area needed to pass a given volume of fluid decreases, and the jet diameter shrinks. It has been observed that the interfacial tension has a pronounced effect on jet constriction.

[10]

OBJECTIVES:

Over the last decade in hydroentanglement industry, the water pressures have been increased from less than a 1000-PSI to today's high pressures reaching 4000 PSI or more. The shape of the orifice however, has essentially remained unchanged. The higher pressures may result in a totally different behavior and the flow may become unstable and drops may be formed instead of a columnar flow. The higher pressures also result in much faster deterioration of the jet strips.

The main objective of this project is the development of the experimental plan with a view to determine:

- Jet profile and jet diameter at various distances from the orifice for various orifices
- The entering jet velocity profile for various orifices

Through a series of experiments, we intend to develop simulation schemes using Fluent to determine the influence of the jet orifice shape and process parameters on the jet properties and the jet velocity profile. We will extend this work to determine the impact of the orifice and the velocity profile on fabric properties.

EXPERIMENTAL APPROACH:

The range of the pressures used in the hydro entanglement process varies and can reach very high pressures. It is well known that, the variations in the pressure can significantly affect the flow properties. To investigate the effect of varying pressures on the flow characteristics of the water jet along with its breakup length and droplet formation from the orifice surface to the rotating belt, two sets of experiments were done to acquire high-speed photographs of the water jets. Visualization results are going to be used to determine the flow regimes, the stability and intact length (undisturbed jet length) of the water jet.

In both experiment sets, experimental apparatus was composed of the Honeycomb Hydroentanglement Machine with operating water pressures up to 1500 psi, 40 holes/inch on the orifice strip and photographic equipment for visualization of fluid body. (Photographic equipment consisted of: two digital stroboscopes, one of which gave a flash with a light duration of about 210 hurts and the other 550 hurts (DT-315 Digital Strobe Volt 12v DC, Shimpo Industrial Co. LTD, in the first set of experiments; in the second set of experiments, high-speed imaging camera with an operating speed of up to 1000 f/s, memory of 1600 frames/1.6s.)

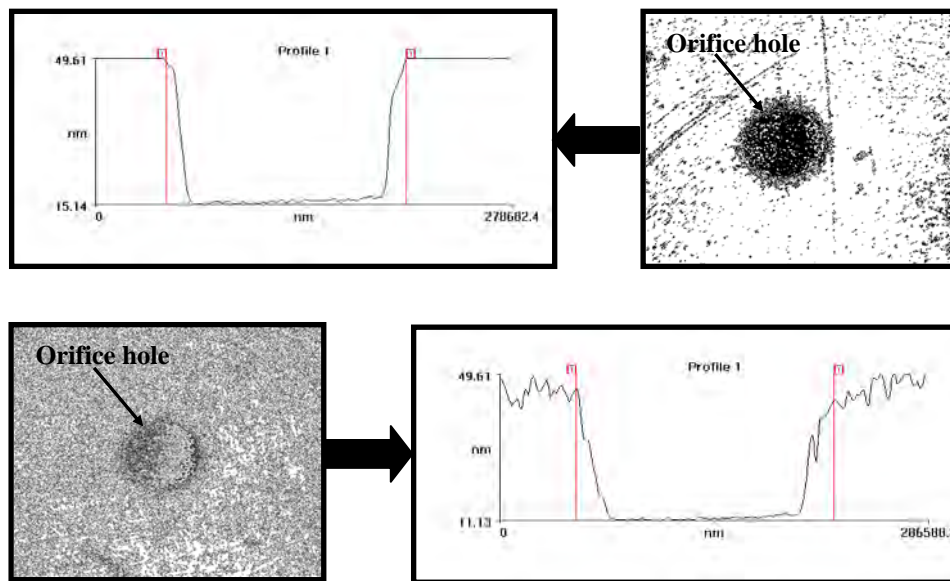
In the first set of experiments, to investigate the effect of the adjacent water jets on the shape of the fluid body jetted from a specific orifice; all the holes along the orifice strip were kept open. The water was pumped to the orifice strip with water pressures of 50 psi, 100 psi, and 150 psi.

In the second set of experiments, to investigate the effect of the parameter of various water pressures on the shape of the water jet, the water was pumped to the third orifice strip with varying pressures within the range of 400 psi-1500 psi. To investigate the effect of the interaction of the flow streams inside the manifold and jets interacting with each other and surrounding air, at first stage the orifices on the orifice strip were taped except one specific orifice hole. During second stage, all the orifices on the orifice strip were kept open.

Investigations of wear & shape change in the nozzle:

To investigate the degree of blockage of the single nozzle, which is a significant problem during flow, images of the nozzles at certain distances from the edges of the orifice strip were taken before experiments so as to investigate the wear and the shape change in the nozzle after the operation. (BURLEIGH Horizon Non Contact Optical Profilometer)

An example of an imaged single orifice hole is shown as below:



The light colors on the images are the high points; the dark colors are the low points. The distance between red bars is the diameter of the orifice hole (nm)

The process of hydro entanglement is based on the entanglement of individual fibers by means of multitude of very fine water jets. Therefore, in order to create these, absolutely uniform

distribution of the water as it emerges from the nozzle needs to be ensured. In hydroentanglement, it is important that the individual liquid streams do not cause streaking or non-uniform fiber entanglement across the layer of fibrous material especially in those areas of the material not contacted by the liquid streams. The water jet has to cause entanglement rather than rearrangement of the fibers. The water jet has to be substantially non-diverging and uniform in width throughout its length under a pressure to effect fiber entanglement, which results in uniform fiber entanglement.

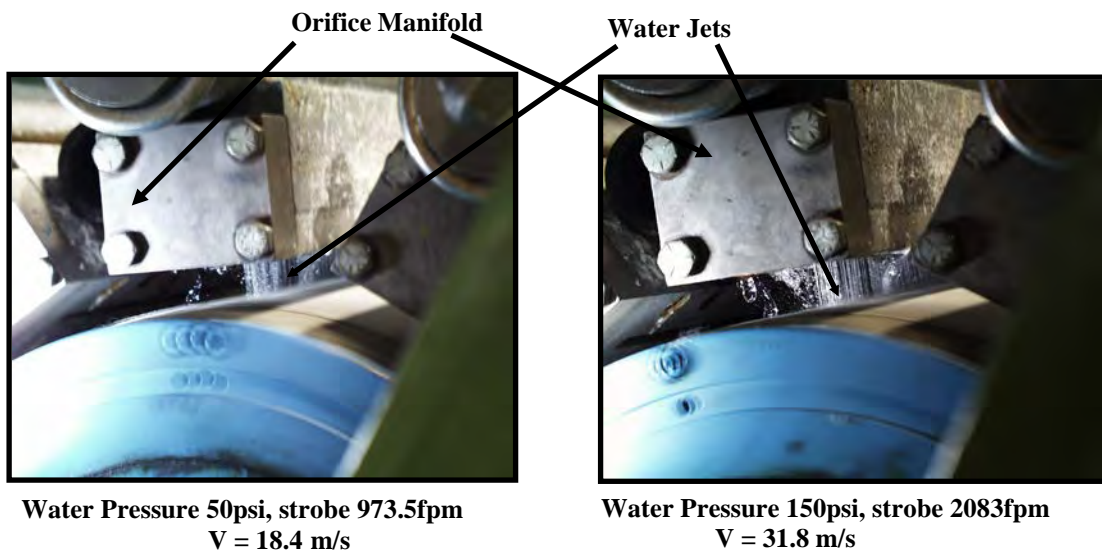
As shown in the images above, wear and shape changes in edge roundness of the orifice holes due to operating conditions, can be easily observed. This phenomenon has a profound effect on the uniformity of the distribution of the water jets. This may result in non-uniform distribution of the water jet; in other words, the jets are not in a columnar, steady manner. As a general rule, the behavior of the water jet is dependent upon the orifice shape. Therefore, it is important to have a rigid orifice strip, resistant to the high operating water pressures.

RESULTS and DISCUSSIONS:

Experiment Set 1:

The aim of this experimental study was to visualize the effect of the parameter of the various water pressures on the flow properties of the water jet by a digital stroboscope, which gave a flash with a light duration of about 550 hurs. Visualization results were going to be used to determine the flow regimes, the stability and intact length (undisturbed jet length) of the water jet.

Typical results are as shown below:



We intended to observe the water jet along with its breakup length (undisturbed jet length, the distance from the orifice surface to the tip of the last segment of the dispersed phase, which is connected to the jet.) and droplet formation.

It is well known that; the surface of a fully developed jet takes on a wavelike appearance at points removed from the orifice. When a vertical jet is formed, it undergoes acceleration under the gravity. As the jet accelerates, the cross sectional area needed to pass a given volume of fluid decreases, and the jet diameter shrinks (jet necking) with increasing distance from the orifice. If the disturbances growing along the jet are large enough, the jet will disrupt into droplets.

We were not able to observe the motion of the water jet along its length from the orifice surface and droplet formation as mentioned above. The believed reasons are as listed below;

- Even at the lowest water pressure (50 psi), the injection velocity of the water jet was so high that we were not able to adjust the same frequency of the water jet motion with the digital strobe. We were just able to slow the motion of the water jet as possible as it could be.
- Most importantly, since the duration of the flashlight of the digital strobe was adjusted manually, we were not able to decide about the best frequency.
- Because of the blockage problem, the water jets were not in a columnar, steady manner.
- The digital camera was found to be insufficient for taking the photographs of the water jet to observe the detailed motion of the water jet.

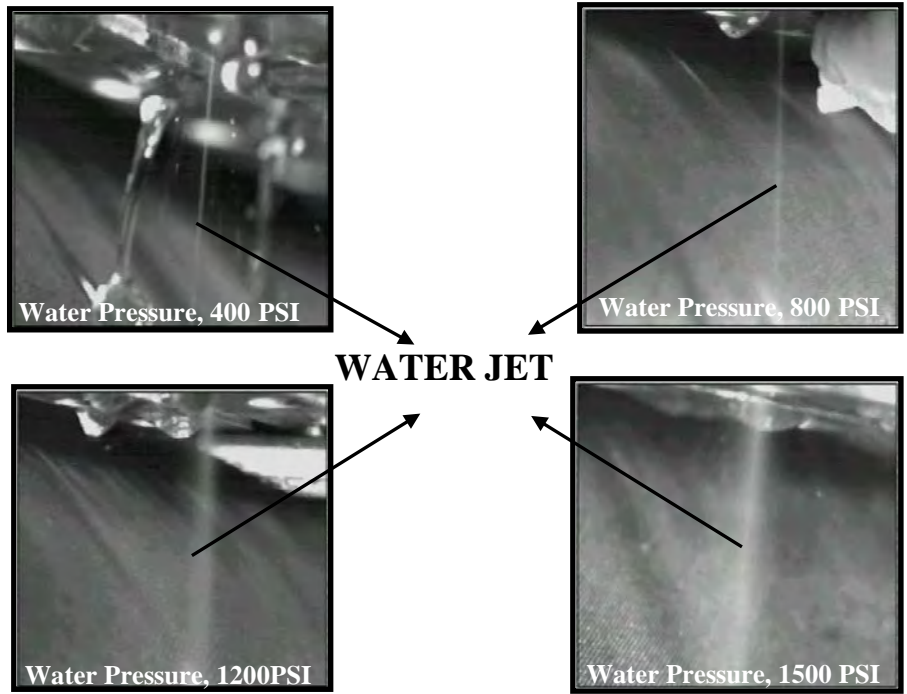
To overcome the problems discussed above, it was decided to use high-speed imaging camera as the photographic equipment for the second set of experiments.

Experiment Set 2:

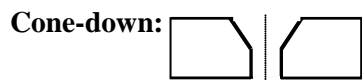
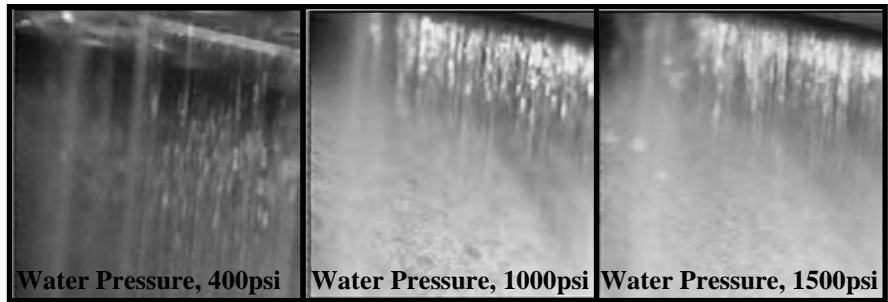
The aim of this experimental study as the case in experiment set 1 was to visualize the effect of the parameter of the various water pressures on the flow properties of the water jet by a high-speed imaging camera with different speeds. Visualization results were supposed to be used to determine the flow regimes, the stability and intact length (undisturbed jet length) of the water jet.

In order to avoid potential blockage of orifices and provide columnar stream of the water jet, the orifice strip was cleaned after each run for different water pressures.

Single orifice hole water jet: (High-speed camera, 1000 f/s)



All orifices open on the orifice strip:(High-speed camera, 1000 f/s)



We intended to observe the water jet along with its breakup length (undisturbed jet length, the distance from the orifice surface to the tip of the last segment of the dispersed phase, which is connected to the jet) and droplet formation.

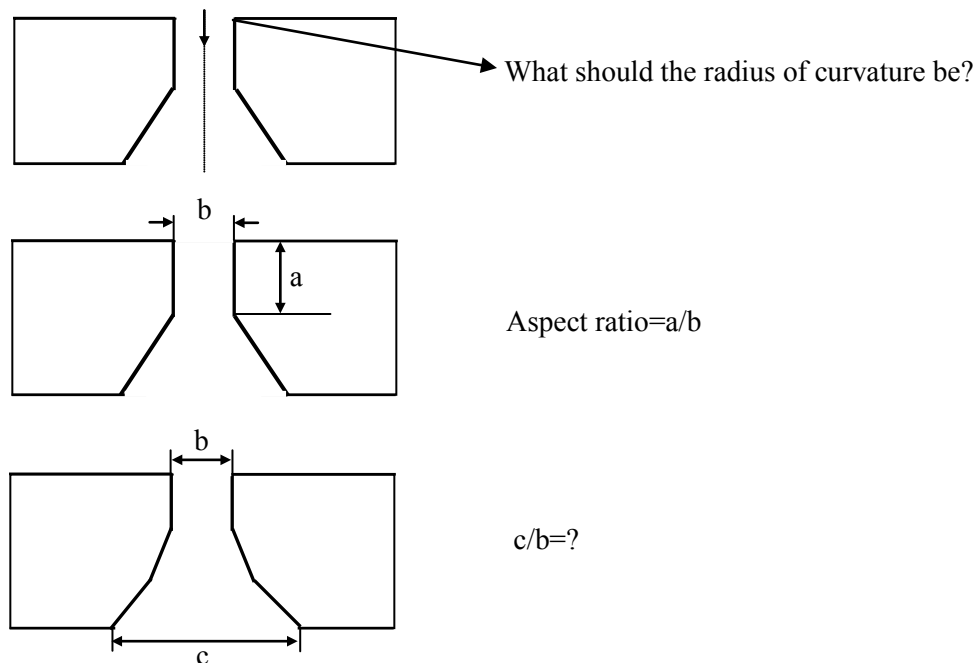
As seen in the images, we were not able to visualize the motion of the water jet along its length from the orifice surface to the end as mentioned earlier. The believed reasons are as listed below;

- Blockage of the orifices was the significant operating problem during our experiments, so uniform distribution of the water jets was not ensured. The water jets were not in a steady, columnar manner.
- The water jets were not distinguished from each other because of the blurriness due to interaction of the flow streams inside the manifold and jets interacting with each other and surrounding air.
- Due to the removal of the seals inside the orifice manifold, water leakage was a significant operating problem during the experiments. This had a profound effect on the uniform distribution of the water jets.
- The speed of the high-speed imaging camera was found to be insufficient for taking the images of the water jets to observe the detailed motion of the water jet. The reason believed is high injection velocity of the water jet

EXPERIMENTAL SETUP:

To overcome the problems discussed above, it was decided to develop a test stand capable of pressures as high as 6000 PSI.

This test stand will allow us to investigate the role of orifice design on the flow characteristics of the single water jet. The different nozzle design parameters as shown in figures below will be investigated.



The investigation of stress-strain on the orifice strip sample is done by ANSYS software to examine the bending and shape change possibility of the strip sample to be used in the experimental stand under high water pressures up to 6000 PSI. Typical results are as shown below:

The strip sample, with a single orifice 0.005" in diameter, is found to have a max stress of **7989** PSI. The strip sample, with a single orifice 0.007" in diameter, is found to have a max stress of **7906** PSI. The orifice strip is composed of 304-type stainless steel. Since the yield strength of this type stainless steel is around 2000 psi with the safety factor taken into account, orifice sample piece, which will be used in the experimental stand, is capable of handling the water pressures up to 6000 PSI [11].

PLANS FOR FUTURE WORK

- Constructing a single orifice experimental stand to produce high-pressure water jets
- Developing model framework using Fluent & undertaking simulations for a variety of orifice shapes. We will compare the Fluent results with those of the experiment. The ability of CFD tools is expected to help better understanding of the nozzle flow.
 - Comparing the model-generated results with those of experimental data.
 - Finalizing the model & establishing the necessary correlations between fiber properties, process conditions & fabric properties.

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