Design of Blow Line Resin Injector for MDF Production

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Preface

The problem addressed in this thesis was presented to me in the winter of 2005 at LARV (labour market day) at Luleå University of Technology (LTU) and was carried out from 28 August 2006 to 16 February 2007 in Sundsvall at Metso Panelboard. I would like to thank my supervisor at Metso Panelboard, Stefan Blom and Tommy Westergård for giving the opportunity of doing this master’s thesis work. At LTU, Magnus Karlberg for great guidance and feedback. I would also like to give a special thanks to Olof Melander (PhD at Metso Paper AB) for the CFX simulations and other fluid dynamic issues, Kurt Schedin at Metso Panelboard RTD for expertise on nozzles and Sören Halvarsson at Metso Panelboard RTD for the knowledge in the latest blow line blending research. Thanks also to all the other staff at Metso Panelboard that helped me with the master’s thesis.

Mats Sundin

Mats Sundin, 2007-02-05
Abstract

This master’s thesis work was carried out at autumn 2006 on Metso Panelboard in Sundsvall (Sweden). Metso Panelboard is one of the leading suppliers of engineering know-how, technology and after-market services for the production of medium density fibreboards (MDF). The objective for this thesis is to design a way of adding the resin into the blow line such that the resin (glue) consumption is reduced.

The resin stands for 30% of the total cost of a MDF board. By keeping the resin consumption down i.e. the mixing as efficient as possible, the total cost of the boards can hence be significantly reduced. The resin binds the fibres in the MDF board together and gives the board its strength. One way to improve the board strength is to increase the number of connections from fibre to fibre, which is achieved by better blending and resin distribution. The resin injector is positioned on the blow line where fibre and steam are flowing from the refiner to the dryer. After a literature survey of the research and the theories about resin consumption, four main issues was identified. These are resin drop size, blow line turbulence, fibre penetration and pre-curing. This led to the design guidelines atomisation, adjustment, placing, angles of the injectors and maintenance.

Because of the lack of information and reports regarding this subject the design could not be connected directly to resin consumption. Compared to today’s design, the design proposed in this thesis is a more mechanical advanced and probably more reliable design with a self-cleaning function. This concept was chosen based on the idea to use one self-controlling resin injector. The injector controls the pressure difference with the plunger that adjusts the column to get the right area of the annular gap. Controlling the pressure difference gives a possibility to minimise the drop size regardless of the flow rate. The plunger will also clean the orifice between resin recipe changes or when the resin flow stops. The plunger will further protect the internal of the injector from fibres in the blow line, when there is no flow through the injector. To ensure the function, flow calculation and computational fluid dynamic (CFD) simulations were performed. Complete drawings were produced for the design so that a prototype can be manufactured and tested in the future.
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1 Introduction

Metso Panelboard is one of the leading suppliers of engineering know-how, technology and after-market services for the production of medium density fibreboard (MDF) and particleboard. The company is an experienced provider of tailored and modular solutions for new panelboard lines, rebuilds and modernisation projects [1].

1.1 Background

Metso Panelboard designs equipment to the board industry (Particleboard and MDF). In Sundsvall they deal with the MDF part of the business. An MDF board consist of wood fibres and resin which is usually added in the blow line. The blow line is a pipe which transports the fibres with steam under pressure from the Defibrator to the dryer. The defibrator (refiner) is a machine that grinds the wood chips under pressure to fibres. The fibre and steam exit the defibrator through the blow valve into the blow line.

Blow line blending is just what it says it will be. The resin is mixed with the fibres in the blow line. The resin flows though nozzles to create a mist of resin to mix in with the fibres. The resin has an approx. cost of 30 % for an MDF board. By keeping the resin consumption down and the mixing as efficient as possible, the total cost of the boards can hence be reduced.

1.2 Task

Reducing the consumption of resin in the finished board is a way of becoming more competitive in the blow line blending industry. The resin consumption is the largest technical drawback in comparison with mechanical blending. Mechanical blending has its on drawbacks with resin spots on the boards, which was the reason why blow line blending was used instead.

The design will be based on technical reports written on the subject and knowledge at Metso Panelboard. The conclusion from the gathered information will later serve as a ground for the design of a resin injector concept. It will also address questions as issues angels, quantity and the way of atomising.

1.3 Objective

The objective for this master’s thesis is to find the conditions that affect the resin consumption and base the design on those. The design will be more adjustable and this will lead to minimised resin consumption with preserved quality.

1.4 Scope

- The thesis will only deal with MDF board manufacturing.
- Only blow line blending will be considered.
- The resin will be of a liquid kind and only UF and MUF resin.
1.5 Work plan

The first task is to gather information and summarise the information. To summarise the knowledge at Metso Panelboard, interviews will be carried out with people who are working with- or have knowledge in the subject. This information will serve as the base for the design paper, describing how a perfect blow line blending system will be constructed. One concept will be chosen of which a prototype will be designed and tested, to evaluate the design paper and the product. The report will be continuously written throughout the project. Presentation will be given in February at Metso Panelboard and at LTU.
2 Theory

2.1 Medium Density Fibreboard (MDF)

For a fibreboard to be called a MDF it requires a fibre moisture less than 20 % at the forming stage and a density higher than 450 kg/m$^3$ [2]. The board is held together with resin and usually Urea Formaldehyde (UF) resin. The density of the board is determined in the hot press where the fibre mat is pressed to the right thickness.

Different types of MDF:
- High Density fibreboard and Flooring (> 800 kg/m$^3$)
- Standard (> 650, < 800 kg/m$^3$)
- Light board (< 650 kg/m$^3$)
- Ultra Light (< 550 kg/m$^3$)

MDF boards can have different kinds of technical properties, physical properties e.g. density, thickens and moisture content. There is also mechanical properties e.g. internal bond, modulus of rupture and processing properties e.g. machinability, surface soundness and screw holding [3].

The raw material used in the MDF depends on what kind of material that is accessible and what kind of board that is manufactured. Commonly used raw materials are pine, spruce, birch and beech. Other raw materials used are bagasse, wheat straw, cotton stalk and sawdust. The kind of raw material that is used affects the quality of the final product.
2.2 The MDF process

The first step in the MDF process is wood handling which includes debarking, chipping and chip and bark handling systems (see Figure 1). In this step, the wood is cutted to the correct size before the refiner as well as separated from stones and other contaminations.

![Figure 1: MDF Process units](image)

The next step is the fibre preparation, which includes the chip washer, steaming bin with Plugscrew feeder, Preheater with discharge screw, Feeder and Defibrator. In the steaming bin the chips is heated by steam to 80-95 °C, and then provides a continuous flow of chips to the plug-screw. The Plugscrew squeeze water out of the chips before the chips enters the pre-heater. In the Preheater the chips are heated to a temperature of 160 °C which makes the fibres soft and easier to separate. The soft chips are then transported into the refiner, where the chips are grinded between two segments into fibres under steam pressure up to 8 bar. In the refiner the fibres are grinned apart, unlike in the paper industry where the fibres are not preheated and thorn apart. The fibres flows with the steam out from the refiner into the blow line and are covered with resin form the resin system (the blow line and resin system is described in chapter 2.3 and 2.5). The fibres drying stage includes one or two dryer cyclones and a Z-Sifter. In the cyclones the fibres are dried with hot flue gas or steam to get the fibres moisture to 5-10%. The Z-Sifter cleans the fibres from contaminates before the forming stage. The forming stage forms the fibres to a mat, which enters the pre-press before it goes into the hot press. The correct thickness of the MDF board is achieved by sending the mat through the hot press where also the resin is cured due to the temperature increase. The
last stage is handling, where the MDF-boards are cut into the correct dimensions, cooled down and stacked for delivery.

2.3 Resin and wax system

The Metso Panelboard resin and wax system (see Figure 2) is an in-line model where all chemicals have separate dosing pumps and flow meters [4]. This system makes rapid recipe changes with minimum material losses.

![Resin and wax system diagram](image)

All the dosing pumps are eccentric screw pumps to get non-fluctuating flow. The pumps that transport the resin to the nozzles can deliver a pressure of 18 bar. Before each resin change a flushing sequence is executed to minimise blockage. The system is fully automatic by programmable logic controller (PLC) and the resin and wax dosage is calculated from the fibre flow. The resin is mixed with hardener, catcher, retarder, water and dye. All chemicals are mixed in the static mixer and sprayed into the blow line. The wax is added at the defibrator inlet.

2.4 Resin and resin additives

The resin (glue) binds the fibres in the MDF board and gives the board its strength. One way to improve the board strength is to add more resin since that give raise to more connections from fibre to fibre. The strength of the board is often measured in internal bond (IB) or tensile strength. The most common resins are Urea formaldehyde (UF) and Melamine urea formaldehyde (MUF), where UF is the cheapest of the two.

**Typical UF resin when delivered:**
- Concentration: 65 %
- Density: approx. 1270 kg/m³
- Viscosity: 100-150 mPas
- pH 25 °C: 7.5-9.0
- Gel time 100 °C: approx. 100 s
When urea and formaldehyde reacts to each other, a polymerisation and condensation binds the fibres together when exposed to heat. The time to cure or gel time is different for every resin and is defined in the technical papers for the resin. The raw materials and recipe also affects the gel time. The raw material can affect the reaction by lowering the pH that accelerates the cure. The hardener is acid that lowers the pH, the typical resin has a pH approx. 7.5 – 9. The storage time for resin in tanks at 20 °C is approx. 8 weeks. However, if the temperature is increased 5-7 °C the storage time is reduced by 50%. The resin can be mixed with a retarder so it does not cure too fast. By adding catcher the amount of free formaldehyde in the board can further be controlled. Wax is added to get a water holdout and dimensional stability in the board if it gets dry. Other chemicals that can be mixed in are dye (pigment) and fire retardants. Water is mixed with the resin to lower the viscosity and make it possible to spray a larger amount of resin without increasing the resin concentration in the board. The finished resin of an average recipe is shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre (dry)</td>
<td>1200-800*</td>
<td>28**</td>
<td></td>
</tr>
<tr>
<td>Resin 1 &amp; Resin 2</td>
<td>1.28</td>
<td>67.3</td>
<td>12 % of fibre</td>
</tr>
<tr>
<td>Catcher</td>
<td>1.11</td>
<td>4.70</td>
<td>3.7 % of resin</td>
</tr>
<tr>
<td>Hardener</td>
<td>1.23</td>
<td>2.50</td>
<td>2.2 % of resin</td>
</tr>
<tr>
<td>Water</td>
<td>1.19</td>
<td>117.6</td>
<td>40 % solid resin</td>
</tr>
<tr>
<td>Resin mixture</td>
<td>0.94</td>
<td>9</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Wax</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Fibre density in kg/m³, **Fibre flow in tonne/h

### 2.5 Blow line

The blow line is a pipe that connects the refiner and the dryer. The steam flow from the refiner carries the fibre to the dryer. The blow line is not just a straight pipe. The shape depends on how the defibrator and the dryer are lined up, and the capacity further gives the diameter. One problem with the design of the blow line is the flexibility in the production the factory wants. They shall be able to run the refiner from 25 % to 100 % production with good results. When the capacity is reduced the pressure and hence the speed in the blow line decreases. This is bad for many parts of the production, such as resin blending since the turbulence goes down, and nozzle design since the spray effect becomes unfavourable.

The blow valve is a segment valve that regulates the flow through the blow line and in second hand the pressure in the refiner. The pressure behind the blow valve is regulated by smaller valves that control how much steam that are put into the defibrator and the preheater, because the blow valve is to insensitive to control the pressure. The pressure difference between the refiner and the dryer makes the steam expand and the speed can in some blow lines increase up to 300 m/s. The high speed in the blow line is advantageous since it prevents build-up of fibre and resin. When designing a blow line several aspects must be encountered for. One of the main design criterias is the resin blending. A good blending can reduce the resin consumption and reduce build-up on the pipe-walls, according to the Chapman model [11] This model is shown in Figure 4 and can be used to optimise the blow line and resin blending. Following this model often results in a reduced diameter of the blow line, which increases the speed.

The amount of fibres in the steam depends on what production rate the factory is running at. If you know the capacity you can calculate the fibre and steam quantity, with an
energy balance over the refiner. The average volume of fibre and steam ratio is approx. 0.2 % [5], but the chance to see-through the fibre flow is small. The mass-energy balances assign energy values to all flows entering or leaving the boundary (refiner). With a factory where the dimensions, pressure and temperature along the blow line are known the speed and flow through the blow line can be approximated. The approximation is based on the energy balance thought the blow line, but it only gives a rough estimation of the speed and flow in the blow line.

**Blow line data from a typical factory with capacity of 30 t/h:**
- **Length:** approx. 20 m
- **Pressure:** Form defibrator house 8 bar to atmospheric pressure in the dryer. Blow valve to the dryer inlet has a 4 to 5 bar pressure drop.
- **Temperature:** Is higher at the beginning of the blow line from, 175 °C to 100 °C depending on the defibrator.
- **Diameter:** 125 mm
- **Speed:** From approx. 100 m/s at the exit of the defibrator to approx. 200-300 m/s at the inlet of the dryer.
- **Flow:** Turbulent, Reynolds number >>2300.

### 2.6 Theories on blow line blending

Optimising the blow line blending is a difficult task since little is known about this process. However, many theories exist which are often based on approximated calculations or experiments, since the condition in a blow line is difficult to model and hence to simulate with computers. Here are some theories:

**Wicking theory** [6, 7] (see chapter 2.6.1)
- Gunnar Gran (Sunds Defibrator AB)
- George Waters (Borden Chemical Co.)
- John Maxwell (Borden International Inc.)

**Modified spot welding theory** [8, 9] (see chapter 2.6.2)
- David Robson (Univ. of Wales, Bangor)
- Jaime Hague (The BioComposite Centre, Univ. of Wales, Bangor)

**Black Box development** [11, 12](see chapter 2.6.3)
- Kelvin M. Chapman (MDFTech) and others

**Resin Distribution (Cell Wall)** [10] (see chapter 2.6.4)
- Warren Grigsby, et al. (Scion, Australia)
2.6.1 Wicking

The word wicking refers to technical fabrics that move liquid away from the skin to the outer surface of the fabric, where it evaporates [6]. This means that the low viscosity resin sets on the surface and penetrating the fibre at the beginning of the blow line. At the end of the blow line fibres connect together and in the dryer steam evaporate from the fibre surface. The steam forces the resin to move to the surface, but the coating is not distributed even since the steam needs to exit somewhere. When the fibres exit the dryer the resin dries on the fibre surface and the temperature decreases from 102 °C to 51 °C because of water evaporation.

According to the theory the resin should be mixed in the beginning of the blow line to get a long mixing time [7]. Higher system temperature results in lower resin viscosity which is advantageous. However, a high temperature can lead to pre-curing and resin hydrolysis which is not good. High turbulence to get good resin distribution and dilution water is favourable since the viscosity decreases and the water works as a thermal insulator in the blow line to prevent resin cure. An experiment performed by G. Gran shows that if the pH can be remained at 7, the strength of the board increases.

2.6.2 Modified Spot-Welding

Modified spot-welding [8, 9] assumes that one small drop binds two fibres together, or the that bigger droplets smears out on the fibres and creates a thin layer of resin on the fibres (see Figure 3). One unwanted condition is when many very small droplets are coupled to one fibre. This will create an uneven distribution on the fibre and a weak fibre to fibre connection.

![Figure 3: Spot Welding, (left) Spot welding, smearing, many to small drops](image)

The droplet size is hence critical for the board strength. Complete coverage will be achieved by smearing or the right drop size.

The drop size is calculated from an empirical equation from particleboard, which is applied to the MDF process. The equation predicts that the drop size is the same as the diameter of the fibre both in the industrial blow line and the pilot plant. In the pilot plant experiments with a 6 meter blow line, the pressure and temperature were measured along the blow line. The speed was calculated to subsonic and high turbulent causes over 40000 fibre to fibre collisions.

According to the theory [8], the best distribution is achieved by many very small drops or larger drops with higher turbulence in the blow line to get the best blending. This means that controlling the drop size and turbulence is critical to get a strong board with less glue. The test at the pilot plant showed that the turbulence gives high grade of collisions which is a benefit for the resin coverage.
2.6.3 Black Box

K. Chapman theory [11] is based on a model (see Figure 4) for blow line blending to optimise and reduce resin consumption. In this model it is assumed that one or several drops generate a fibre to fibre connection to get a good MDF panel. The drop size is very important and a steam atomisation is preferable to get the right drop size at any fibre flow. The drop size shall be as small as the atomisation can handle and it is important to be able to remain that size even if the resin flow is decreased. Chapman often reduces the blow line diameter to get higher speed in the pipe and to increase the degree of turbulence. With this model Chapman claims that he has reduced the resin consumption with up to 20 to 25 % [12].

![Figure 4: K. Chapman's model of blow line blending optimisation](image)

The final step of Chapman’s model shows the results of aggregation and separation. The size of the droplets determines whether the mixture will aggregate or separate (see Figure 5). Large droplet will more likely bond two fibres and resist the shear force, but will on the other hand also more likely aggregate (build-up) and cause resin spots on the board. Smaller resin droplets will more probably separate with increased speed in the blow line. The fibre length also influences the shear force which separates two fibres. Shorter fibres are less likely to separate then larger ones.
It is difficult to draw any conclusions from Chapman’s journals since this theory has not been validated. For instance he claims that the sound of speed in the blow line is 500 m/s when in fact it is rather around 200-300 m/s. This and some other strange figures in his journals make the conclusions unreliable. However, the scope of this theory is large and addresses issues from the fibre quality to the outcome of the fibre and resin. This model has been used to optimise the blow line. Correct speed together, with small drops reduced the consumption of resin because of better blending.

2.6.4 Resin Distribution (Cell Wall)

By the use of a Confocal Laser Scanning Microscopy (CLSM) and fluorescence, Scion has been able of taking pictures of the fibres at three different stages in the process [10] The images show how the resin is covering the fibre and penetrating the outer surface of the fibre. The three stages are after the blow line, out of the dryer and in the finished board. In the experiment they change the nozzle pressure, production rate and steam flow to the refiner. The objective of this experiment was to show that changing process parameters alter the resin distribution.

One conclusion of this experiment is that by changing these process parameters the coverage on the fibre is changed. It also shows that penetration of resin through the fibre wall is possible through the whole process. There is no comment regarding whether the penetration is good or bad, only how the penetration is in the three stages of the process. The different variations of the process showed that high turbulent (high steam flow) gives better coverage through the fibre. Nozzle pressure and production rate gives small changes in the coverage. Increased turbulence in the blow line is one way to achieve better mixture and hence reducing the resin quantity.

2.7 Droplet size

Several studies regarding the droplet size exist within the blow line blending industry [8, 11]. The theories and thoughts in this subject are contradictory, what the perfect drop size should be. Shall the drop size be as small as possible, shall it be based on the fibre dimensions or does the size not matter? The problem is to make sure that the finished board will have the right properties. If the drop size is known and does not vary with time, optimisation of the process is possible. The droplet size can be measured by different methods. Below some of the most used are listed.

Drop size is usually expressed in microns (micrometers). The most popular mean and characteristic diameters and their definitions are [13].
• Volume Median Diameter (VMD, $D_{v0.5}$ or MMD): 
  A median value of drop sizes in terms of the volume of liquid sprayed. The Volume 
  Median Diameter drop size when measured in terms of volume (or mass) is a value 
  where 50% of the total volume of liquid sprayed is made up of drops with diameters 
  larger than the median value and 50% with smaller diameters.

• Sauter Mean Diameter (SMD or $D_{32}$) 
  A mean value of the fineness of a spray in terms of the surface area produced by the 
  spray. The Sauter Mean Diameter is the diameter of a drop having the same volume-
  to-surface area ratio as the total volume of all the drops to the total surface area of 
  all the drops.

• Number Median Diameter (NMD or $D_{N0.5}$) 
  A median value of drop sizes in terms of the number of drops in the spray. This 
  means that 50% of the drops by count or number are smaller than the median 
  diameter and 50% of the drops are larger than the median diameter.
2.8 Atomisation nozzles

If the needed drop size is known, the atomisation in the nozzle shall be designed to achieve this. Fluid properties affecting the spray are surface tension, viscosity and density. The surface tension tends to hold the liquid together and keeping it from breaking up into drops. The viscosity has the same effect as surface tension and density causes the fluid to resist acceleration [14].

Table 2: Atomisation nozzles [15]

<table>
<thead>
<tr>
<th>Atomisation type</th>
<th>Drop size [μm]</th>
<th>Commentary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>20-1000</td>
<td>High supply pressure</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>50-500</td>
<td>Limited liquid/air ratios</td>
</tr>
<tr>
<td>Rotary</td>
<td>10-200</td>
<td>360° spray pattern</td>
</tr>
<tr>
<td>Expanding gas</td>
<td>20-140</td>
<td>Liquid backup into air line.</td>
</tr>
<tr>
<td>Ultrasonic atomisation</td>
<td>1-5, 30-60</td>
<td>55 kHz at 0.12 l/min, 50 kHz</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>0.1-1000</td>
<td>Liquid electrical properties</td>
</tr>
</tbody>
</table>

2.8.1 Pressure spray

Pressure spray nozzles use pressured flow through one (see Figure 6) or many small holes; the shape determines the spray pattern. The droplet size depends on flow, pressure difference over the nozzle and spray pattern (diameter and shape of the hole) [16]. Another atomisation technique is to direct two or more jet of liquid against each other, to get a spray of droplets.

Figure 6: Pressure spray nozzle (VeeJet [16])

Advantage in resin blending
- Easy design
- No extra energy is added in the atomisation
- Handle large flows

Disadvantage in resin blending
- To get small drops the pressure different need to be at least 80 to a 100 bar.
- No control over the drop size if the resin flow decrease or viscosity changes.
2.8.2 **Pneumatic**

Pneumatic nozzle uses air pressure or other gas under pressure to break the liquid to droplets (see Figure 7). The friction between the acceleration high-speed gas and the low speed liquid generates the break-up of the liquid to drops [14].

Figure 7: Pneumatic atomisation with gas

Advantage in resin blending
- The steam from the refiner system can be used for atomisation of the resin.
- Good atomisation
- Adjustable drop size

Disadvantage in resin blending
- Need extra energy for atomisation, compressed air or steam.

2.8.3 **Rotary (Mechanical)**

*Rotary atomisation* (Mechanical nozzles) uses a rotation disc (see Figure 8) that the liquid is dropped on. The centrifugal force results in a film of liquid, and when the film reaches the edge the liquid breaks up to droplets [14].

Figure 8: Mechanical atomisation

Advantage in resin blending
- Control over the drop size by regulating the rotating speed.
- Good atomisation

Disadvantage in resin blending
- The size of the nozzle
- The constant motor spinning
2.8.4 Expanding gas

Expanding gas atomisation works with an expanding gas that added to the liquid before the nozzle (see Figure 9). When the gas and liquid reaches the nozzles the gas expands and the liquid breaks up to drops.

![Figure 9: Expanding gas atomisation](image)

Advantage in resin blending
- Good atomisation
- More adjustable and steam works well as extra atomisation energy.
- Steam is also available in every refinery system.

Disadvantage in resin blending
- The steam adds extra heat to the resin and may cause problems with pre-curing and blockage of the resin flow.
- Pulsation

2.8.5 Ultrasonic

Ultrasonic atomisation relies on an electromechanical device that vibrates at a very high frequency. Fluid passes over the vibrating surface and the vibration causes the fluid to break into droplets, see Figure 10 [14].

![Figure 10: Ultrasonic atomisation](image)

Advantage in resin blending
- Really small drops

Disadvantage in resin blending
- Only for low viscosity liquid

16
• Only for small flows, less then 1 l/min

### 2.8.6 Electrostatic

Electrostatic atomisation exposes a fluid to an intense electric field between the charged atomiser and grounded work piece (see Figure 11). The charge transfers to the fluid and repulsive forces between the atomiser and the fluid tear the droplets from the atomiser and send them toward the work surface [14]. The drop size depends on three factors; electric field strength, liquid flow rate and fluid properties (density, electrical properties, etc.)

![Figure 11: Electrostatic atomisation](image)

Advantage in resin blending
- None

Disadvantage in resin blending
- Hard to apply this technique
- Only for small flows

### 2.9 Resin injectors

The final stage of the resin and wax system is the resin nozzles which sprays the resin on the fibres (see the end of the yellow line in Figure 2). When blow line blending is used, the nozzles are placed on the blow line and due to the turbulent flow the resin is then mixed with the fibres. The flow of resin through the nozzles is depending on the resin recipe and the fibre flow. Often, nozzles of pressure atomisation type are used (for details see chapter 2.8).

#### 2.9.1 Metso Panelboard resin injectors

Today Metso Panelboard are using 2 to 4 water-cooled nozzles with pressure spray atomisation (see Figure 12). The pressure difference is between 3 to 6 bar and this kind of nozzle gives a droplet sizes of approx. 0.8 to 1 mm (see Appendix 1). Water-cooling is not use in every factory.
One benefit with water-cooling is when the factory is not running resin through the injectors. Water-cooling prevents the temperature in the injectors from increasing, and hence resin from curing in the injectors. In regular production the resin takes care of the cooling of the nozzles.

In the first version of blow line blending the resin nozzle and blow valve was one part, and the resin was added just after the blow valve. The design consisted of a hole that the resin flows through, with a water-cooled coating. The nozzles were positioned just after the blow valve where the degree of turbulence and speed was highest, and that is probably one success factor. The resin atomisation was created by a hole which was drilled out in different dimensions depending on what capacity the factory needed. As the capacity of the refinery increased this design could not deliver the needed flow, and was hence replaced. Maintenances is also difficult to perform on these resin nozzles.

The third nozzle that has been designed is a regulated pressure spray nozzle. The nozzle is placed on the blow line, just like the one used today. The nozzle can be regulated with a crank that controls the sizes of the nozzle hole. The crank controls the pressure drop in the nozzle, which controls the drop size. The idea was to have at least two nozzles, when one is cleaned the other one can be used. This resin injector is also water-cooled.

2.9.2 Other resin injectors on the market

Kevin M Chapman has developed an own resin nozzle, see Figure 13. He uses gas atomisation to create a spray of resin on the fibre. The gas is steam and with this technique small droplets can be achieved regardless of the resin flow, pressure or temperature that is present (the stream flow is regulated). The nozzle is also self-cleaning.
The nozzle is equipped with an air-controlled plunger to prevent coating or nozzle blocking. One benefit with this design is the control of the droplet size and self-cleaning. Disadvantages are the extra energy that is needed for atomisation and control of the plunger. The heat from the steam can be a problem due to resin cures in the nozzle. There is no water-cooling option.

IMAL is a competitor to Metso Panelboard that also deliver glue kitchen and resin injectors. They use a number of pressure atomisation nozzles (up to 10 placed) evenly distributed over 2 meter and around the blow line. Each injector has its own ball valve connected to the blow line. One idea of using several nozzles is that they can be turned off during low production speed when they are not needed. They can also be dismantled and cleaned under production when the ball valve is closed. The resin nozzles have a water-cooling function.

In one factory the placement of the resin injectors depends on what resin they use (because of the curing time of the resin). When a fast curing resin was used the resin was added later in the blow line to prevent it from curing in the dryer.

In other factories a mixing zone has been designed by decreasing the diameter of the blow line to get a higher speed. With the increased speed the risk of build-up is reduced as well as resin spots on the board.

**2.10 Benchmarking on nozzles not used for resin blending**

Following nozzle manufacturers were investigated for suitable nozzles. The general search scope was large flow capacity, adjustable and cleaning.

**2.10.1 Duesen-schlick**

- Series 631 (see Figure 14)
  - Series D10.555
  - Spring-Biased
  - Pressure Nozzles
  - 20 l/min

Extra:
- Closes when there is no flow of liquid.
- Have been used for blow line blending.
Series 0/2-0/60 (see Figure 15)
• Two-Substance
• Lance Nozzles
• Internal or external mix
• 60 l/min water
• 920 m³/h, 6 bar air
• Drop size 70 to 80 microns

Extras:
• Adjustable to variable liquid flow
• Cleaning plunger
• Specified for air

2.10.2 Turbosonic

Turbotak Q07-1417 (see Figure 16)
• Two-Phase Nozzles
• Internal mixing
• 1 Nozzle, 1 orifice 20 mm
• 150 l/min at 5 bar
• Steam 1500 kg/h at 6 bar
• Drop size, 50 microns

Extra
• Pulsation effect when the hot steam meets the cold resin.
• The steam and resin pressure shall be kept at 0,5 bar difference in favour of steam.

2.10.3 Delavan - Spray Technologies

Two Swirl-Air nozzle (see Figure 17)
• Internal mixing
• 112 l/min water, 3,58 bar
• 33 kg/h air at 2 bar
• Drop size 200 - 350 microns

Extra
• Complex internal.
• Pulsation effect when the hot steam meets the cold resin.
• Specified for air
2.11 Related technology

To learn more about different ways to distribute small droplet, related technologies have been studied. Fire extinguishers were studied because of the fine spray they use. A heavy oil burner is another technology to studied because of the high viscosity liquid and the degree of atomisation in the area.

2.11.1 Fire extinguisher

The conclusion shows two angels of the subject [17]. It was showed that small drop was advantageous because of the larger cover area that cools the fire gases faster. The small droplets can better absorb the heat radiation (see Figure 18) and it leads to reduction of oxygen in the air as well as temperature. On the other hand, larger drops have the possibility to reach and cool the fuel. To reach the fuel, greater kinematics energy is needed and larger drops are one way to achieve that. Pressure atomisation is used in fire extinguishers.

Figure 18 Evaporation time vs drop size [18]

2.11.2 Heavy oil burner

To be able to use raw oil as a fuel in boilers atomisation is critical because of viscosity and the effectiveness of the combustion. Pressure nozzles were the most used but the pressure needed was too high, and hence mechanical nozzles is used. The mechanical nozzle uses a rotating disc and produced small drops without high flow of oil. The next step in optimising the combustion was steam atomisation nozzle. As for the mechanical nozzle it produced very small drops with an easier design. In the oil burning process, drop size is not critical. It is rather to get a good mixture with small drops that burn fast and larger to get a longer flame. If the atomisation only produce small drops the foul should burn up too fast and the temperature on the nozzle becomes too high. The steam atomiser burners pre-heat the oil to 60 °C and uses about 5% steam of the mass flow of oil for atomisation energy.

2.12 Testing MDF boards

To determine the MDF board properties a series of tests are performed. According to EN 622-5:1997 the 12 mm test board shall be for general purpose in dry climate and have these properties tested. Following properties is for determine the board quality; thickness swelling over 24h, internal bond (IB), modulus of rapture and modulus of elasticity.
Another test that is performed is the density profile, which can be an important issue for some cases due to its direct connection to IB. The density profile is measured by a machine, and the density is shown as a function of the thickness (see Figure 19). The density is often higher at the surfaces of the board because the resin cures faster there. This is preferable if high tensile strength in bending is needed.

![Figure 19: Density profile](image)

The internal bond is tested in a tensile strength test see Figure 20. For a board with a thickness of 12 mm the IB shall be at least 0,60 N/mm² according to standard EN 622-5:1997.

![Figure 20: Tensile strength test](image)

Thickness swelling (TS) is measured over time. The board samples is lowered in water of 20 °C for 24 hours. For a 12 mm board the swelling shall not be over 15 %.

Fibre samples are also taken to measure the size of fibres after the dryer. This is useful to see how the refiner works, especially when new raw materials are tested. Kjeldahls method [19] gives another measure of the resin quantity on the fibres. Here, the nitrogen content in the fibre as well as in the resin are measured and then compared by the fibre sample after the dryer. This is done to be sure how much resin that has been added and the method is a standard procedure for many organic materials. To take a fibre sample and look at the resin coverage is done with microscope and a colored resin. The problem is to look at a large amount of fibre to get it statistically correct. This can be
done if a computer scans a large amount of fibres. In chapter 2.6.4 the resin coverage *in the fibre* has been measured using this technique. One way of testing a new resin injector is to do it in a factory by switching the old and the new. It is however difficult to keep all variables constant and hence to evaluate the result. One way of measuring the blending quality is by looking at the IB on the board.

An experiment was carried out at Metso Panelboard research plant. The idea was to investigate if there is possible to enhance the quality on the board (IB and TS) by small changes of the pressure difference in the nozzle and the resin concentration. The result of this test was that it was not possible to see any enhancements in quality on the board (see Appendix 6).
3 Design guidelines

In chapters 3.1 and 3.2 the conclusions about the most important issues and thought of the theories, interviews and journals reviewed, on the subject blow line blending and resin injectors are given.

3.1 Blow line blending

Drop size
The drop size influences the blending. With small drops the mixing should be better and the change to cover every fibre. However, it could not be concluded whether it is the atomisation or the turbulence in the blow line that gives the right size droplets. The optimum drop size for such situation could by this study not be found.

Turbulence
A good speed and turbulence reduce build-up on the pipe-wall, how important it is and how it affects the resin consumption could not be found in this study. The blow line shall be designed to create high degree of turbulence and speed in the blow line since that is preferable. In the blow valve the velocity goes up and the concentration of fibre are higher then in the blow line. It is hence possible that the resin shall be added there.

Penetration
When the soft fibres is mixed with the resin an amount of resin penetrates the cell wall of the fibre. A small amount of resin will return to the surface but some resin will remain inside the fibre after the press. This might not be wanted if the fibres shall smear the resin between them. For optimal blending all the resin should be on the surface to bind the board. One reason why penetration occurs is that fibres become softer from the heat and the low viscosity of the resin. If water is dissolved in the resin the viscosity will go down and maybe the drop size can be a reason of penetration. The only thing that can be proved is that there is penetration but how it affects the resin blending and how it occurs could not be determined in this study.

Pre-curing
Pre-curing means that the resin is starting to cure because of the heat from the blow line and dryer. The UF resin that is used start curing at 60 °C and the blow line has a temperature of approx. 100 °C to 170 °C. The gel time for the resin is depends on several things. One thing is dilution water that increases the gel-time. Along the blow line the water will evaporate and the gel-time will decrease. Even if the time in the blow line and the dryer is short it will affect the resin. This can be the reason for increased resin consumption in blow line blending compared to mechanical blending.

3.2 Resin injector

The new design of the resin injector shall take the subjects under consideration under the concept design. The subjects are based on the conclusions from the previous chapter and serves as the foundation for the road map.
Atomisation

Today Metso Panelboard uses pressure nozzles with a pressure difference between 3 to 6 bar. This gives a drop size between 0.8 mm to 1 mm (see Appendix 1) in quiescent air. The blow line has no normal conditions, the turbulence and speed will help the atomisation process. One way of getting smaller drops size is by using steam which is available from the refiner process. With steam the drop size can be reduced significantly. The heat from the steam can be a problem, which is something that needs to be investigated.

Adjustment

The board manufacturer wants to have a flexible product flow, from 25 % to 100 % with satisfying results. One problem with today’s solution is to find the right nozzle for that span, which means that an adjustable resin injector is to prefer. When the production is low the velocity and fibre quantity is low. These results in lower turbulence compare to full production. The flow through the nozzles is lower and the pressure difference is smaller and hence that the droplets size increases or there is no atomisation in the current solution. The adjustment in the resin injector shall be able to control the drop size to match the production and the fibre.

Injector placement

To get as long mixing time in the blow line as possible, the resin injectors should be positioned as close to the blow valve as possible. If the placement is 1 or 5 meters after the blow valve should not have any affect on the final product. To find the best position, experiments must be carried out. Notice that it can be preferable to position the injector at the blow valve. The temperature can however be a problem if the resin is injected into the blow valve. Hence, a new design of the blow valve is needed if the resin injector shall be placed there.

Angles of the nozzles

The angle of the injectors can be important if the concentration of fibre is low or when fibre flow variations are large. The simulation (see Appendix 1) shows that 1 mm and 200 μm drops will hit the other side of the blow line. However, the simulations do not take the fibre collisions under consideration. If the drop size is larger then 200 μm the injectors shall be angled with the flow to avoid hitting the opposite wall. This holds also if the fibre flow has low concentration or if the fibre velocity is low.

Cleaning

A nozzle which is self-cleaned during production is preferable. A plunger will be designed to clean the nozzle from coated resin and to close the nozzle hole, so no fibre from the blow line can get trough. To increase the function of the injector and get a more reliable production.


4 Roadmap

In the roadmap the most important needs and requirements are documented for the new resin injector. This was done to help the concept generation and evaluation processes.

<table>
<thead>
<tr>
<th>Needs/requirements</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase the reliability under production.</td>
<td>Easy design, large orifice and physical cleaning of orifice.</td>
</tr>
<tr>
<td>Self-cleaning during production.</td>
<td>No need to stop production for cleaning.</td>
</tr>
<tr>
<td>Always same droplets size.</td>
<td>Due to temperature, resin flow and blow line pressure the drop size is kept the same size.</td>
</tr>
<tr>
<td>Handle the same flow as current nozzles.</td>
<td>40 l/min to 150 l/min</td>
</tr>
<tr>
<td>Angle of the injectors.</td>
<td>If the solution has large drops the injectors shall be angled with the flow to avoid hitting the other side.</td>
</tr>
<tr>
<td>Number of injectors.</td>
<td>Be kept down for service and maintenance.</td>
</tr>
<tr>
<td>Be placed as close to the blow valve.</td>
<td>To get a good mix time between the fibres and resin.</td>
</tr>
</tbody>
</table>

The design of the new resin injector(s) shall be easy to adapt to current resin system and extra cost have to be kept down. The design shall facilitate service under production stops and have replaceable parts.
5 Design

5.1 Concept generation

The brainstorming sessions around the roadmap were carried out which resulted in ideas that was formed into concept. Information from interviews and benchmarking was also taken under consideration.

5.1.1 Idea 1 – Spring pressure

The idea for this design is to control the pressure difference in the nozzle tip regardless of what flow is going through the nozzle, without outer influence. The spring controls the pressure difference (see Figure 21) and will therefore open more when flow (pressure) increases. The plunger will be fully closed when there is no flow and will also clean the nozzle and protect it from fibre. Another benefit is if the annular orifice (see Figure 22) clogg or resin lumps get stuck in the column the plunger will just open more and hopefully clears the orifice.

Solves:
Cleaning of the orifice
Self-adjusting to variation in flow
One injector, easy to maintain

Left to do:
Atomisation
Drop size
Calculation on the annular orifice size
Leakage between the cylinder and the wall
5.1.2 Idea 2 – Gas atomiser

The idea shown in Figure 23 is to get more control over the atomisation, flow variations and the cleaning. The small annular orifice is designed to create a pre-film and therefore get a better atomisation. The steam is used to break-up the resin into drops. The plunger in the middle is motorised and controls the pre-film length and cleaning.

Solves:
Cleaning the orifice
Variation in flow
One injector, easy to maintain
Adjustable drop size

Left to do:
Control and cleaning of plunger
Nozzle design, pre-film and flow
Steam to resin ratio
5.1.3 Idea 3 – de Laval injector

The difference between this injector compared to Idea 2 is that the annular orifice is changed into a sharp edge hole and the steam annular orifice is a de Laval design, see Figure 24 at the tip of the nozzle. To get higher speed difference between the resin and the steam, a de Laval design is used. Then the steam velocity reach above the speed of sound, which is not possible with a conventional nozzle. The design is easier to manufacture then idea 2 and to preform calculations on, because there is no pre-filming. The design is also more reliable then the idea 2, because the plunger can clean the whole resin pipe. The drawback is the large drop size and that the design is not adjustable. The plunger is controlled by a pneumatic cylinder since it shall only be on or off to clean the orifice. Compressed air is available at every factory with a pressure of 6 bar, to control the pneumatic cylinder.

Solves:
Cleaning the orifice

Left to do:
Control and cleaning of plunger
Nozzle design, de Laval design
Steam to resin ratio
5.1.4 Idea 4 – Valve Injector

The idea with this design is to be able to shut off one or more of the nozzle when the resin flow is decreased below a certain threshold. The idea is to redirect the resin with a plunger that leads resin to the next injector. The injectors will be equipped with 4 manufacture nozzles with the combination of 50, 50, 30, and 20 l/min. The combination of the injectors gives the correct pressure difference and spray effect. The resin injectors should be connected in a chain so the flow passes through every injector. The resin cools the injectors that are not in use, and when the flow stops all the injectors will be closed. Pneumatic cylinders will lift the plungers. When a new combination is needed all the injectors are opened and flushed, to prevent it to get stuck in the closed position (see left Figure 25).

Figure 25: Idea 4 - Valve Injector (The left is open and the right is closed)

Solves:
Cleaning the orifice
Cooling
Adjustable to resin flow

Left to do:
Control of the plunger
System design and pressure drop in the system
The risk of get stuck in the closed position
5.1.5 **Idea 5 – Injector magazine**

The idea in this design is to use a “sled” (A in Figure 26) to make the nozzle accessible from the outside for cleaning and change. The “sled” will be motor controlled and will punch the clogged nozzle out letting the other one to take over.

![Figure 26: Idea 5 - Injector magazine](image)

*Solves:*
- Maintenance under production

*Left to do:*
- Gasket, between the injector to “sled” and “sled” to blow line
- Motor control
5.2 Concept evaluation

In the evaluation process the ideas were evaluated to continue into concept. The first idea evaluated was idea 4 – magazine injector, at a meeting with the supervisors 06-12-01. The idea was judged to be too complex, and did further just meet one goal in the roadmap. The other four ideas were evaluated further and formed into concepts. To narrow the evaluation face, two more ideas were discarded. It was decided that the evaluation process should continue with one pressure and one steam atomisation idea. Hence, Idea 1 and 2 were chosen because they were more complete and more interesting. Idea 4 were rejected due to its complex controlling system to be able to find the correct combination and to secure that the plunger did not get stuck in its closed position. Idea 3 is a simple design, but the steam rate should be large and hence a larger quantity of injector should be needed. The Duesen-schlick nozzles were the only commercial manufacture nozzles that would work and was further evaluated in the Pugh matrix (see Table 3). The remaining manufacture nozzles were discarded since they did not reach the requirements in the roadmap and the problem with internal mix causes pulsation.

5.2.1 Concept 1 – Pressure spring injector

The concept is based on the idea to use one self-controlling resin injector (Idea 1). The plunger that decrees and enhances the annular controls the pressure difference. The plunger will clean the orifice between resin recipe changes or when the resin flow stops, and protect the internal of the injector from fibres.

The areas needed to get a 4 bar pressure difference ($\Delta p$), with the flow variation from 40 l/min to 150 l/min ($Q$), is given by Bernoulli's equation

$$Q = \mu \cdot A \cdot \sqrt{\frac{2\Delta p}{\rho}}$$

where the flow friction coefficient ($\mu$) was set to 0.62 because of a sharp orifice and the density ($\rho$). The flow friction coefficient was not suited for an annular orifice, but the equation was evaluated with computational fluid dynamic (CFD) simulations in the software CFX (see Figure 27 and Appendix 4) The model has the correct area to get a 4 bar pressure difference at a flow of 40 l/min. Figure 27 shows a 3.6 bar pressure difference, but the simulation nozzle had a slightly larger gap compared to the analytical model which showed 4 bar pressure difference.
One challenge with this concept is how to prevent resin leakage between the cylinder and the wall. A membrane solution which separates the pressure chamber from the spring chamber is suggested (see Figure 28). The membrane will be made of a chemical resistant rubber due to good elastic performance. The approximated stroke of the plunger is somewhere between 7 to 10 mm.

Goals achieved:
- Self controlling to resin flow
- Reliable
- Protected from fibres when not in use
- Cleans the orifice
- No extra cost on the resin system
5.2.2 Concept 2 – Steam injector

This concept is based on the idea of atomising with gas or steam. Steam helps the atomisation and hence gives small drops without higher resin pressure. Due to the high velocity and expansion of the steam at the annular orifice, the small film of resin break up to drops. The steam is the same as for the refiner, where the pressure is about 10 bar controlled by an on/off valve. The nozzle orifice is designed to give the correct amount of resin and steam ratio and at the same time as high steam velocity as possible. Pumps control the resin flow to the nozzle, adjusting the plunger controls the length and thickness of the resin film and will result in more control over the drop size. To get a good atomisation the resin velocity has to be kept down, which will result in a large annular orifice to get a large area. At the tip of the plunger there is a risk of build up with resin since there will be a backward flow present. An electrical motor controls the plunger which adjusts the pre-filming thickness and cleans the orifice (see Figure 29).

![Figure 29: Concept 2 - Steam injector](image)

The equations used to design this nozzle only gives an approximation of the drop size. The Equation (2)-(3) is usually used for water and compressed air which for concept 2 is replaced with resin and steam. The Equation (2) has got pre-film as a variable \(D_p\). By El-Shanawany & Lefebvre [20]

\[
SMD = 0.073 \cdot \left( \frac{\sigma_L}{\rho_A \cdot U_A^2} \right)^{0.6} \cdot \left( \frac{\rho_L}{\rho_A} \right)^{0.1} \cdot D_p^{0.4} \cdot \left(1 + \frac{W_L}{W_A} \right) + 0.015 \cdot \left( \frac{\mu_L \cdot D_p}{\sigma_L \cdot \rho_L} \right)^{0.5} \cdot \left(1 + \frac{W_L}{W_A} \right)
\]

(2)

were \(\rho\) is the density, \(\mu\) the dynamic viscosity, \(\sigma\) the surface tension, \(A\) the annular orifice area, \(Q\) the volume flow, \(W\) the mass flow and \(U\) the velocity. Subscript \(L\) represents liquid while subscript \(A\) represents air. The equation for a convergent nozzle by Kim & Marshall [15] with the area of the annular orifice that surrounds the resin flow \(A_a\)
In Equation (3) the variable \( m \) is given by

\[
m = \begin{cases} 
-1 & \text{for } W_A/W_L < 3 \\
-0.5 & \text{for } W_A/W_L < 3 
\end{cases}
\]  

The largest influence in both equations is the speed difference between the resin and the steam. The nozzle design was therefore dimensioned as follow. The steam is assumed to have a pressure of 10 bar and a temperature of 170 °C. The speed shall be kept as high as possible, which means that the pressure drop at the end of the nozzle shall be as high as possible. The flow of steam that is used in the design is 5 % of the mass flow of resin in order to have a specific flow of steam and to calculate the area for the orifice (see Appendix 3 - Table 7). This results in a mass flow of 500 kg/h at the highest flow of resin, which can be compared with the total steam consumption which is 20 tons/h. The total change in consumption is hence reasonable, especially since the steam is “free” if the factory uses waste products to create steam. However if the result of gas atomisation should reduce the resin consumption it profitable anyhow.

To get a high velocity difference between resin and steam, the resin flow shall have a low velocity. In the Equation (1-4) the resin velocity is maximum 30 m/s with a 3 bar pressure drop at the orifice. Equation (1) together with these limitations gives the area of the annular orifice. Another parameter that affects the design is the pre-filming that has been set to 1 millimetre. Hence, the annular orifice has got to have a large diameter in order to get the correct area.

The result from the Equation (2) and Equation (3) with a variation in resin flow gives an approximated result on the drop size, see Figure 30 and See Appendix 3 for the calculations.
The area between the steam and resin channel is designed to create spacing between the steam flow and the resin flow. This space can be filled with air, like a thermos or a water flow. This is to secure that there is no heating of the resin injector, which will lead to coating in the resin channel.

Goals achieved:
- Adjustable drop size
- Reliable
- Cleans the orifice
- Protected from fibres when not in use, if the plunger position right.

Future work:

The vision with this concept is to get a reliable resin injector with good atomisation and low steam consumption. The motor controlled plunger helps the productivity by cleaning the orifice, but also controls the drop size. Reaching this goal, the nozzle design has to be verified by simulations and validated by measurements. Simulations will help to find the optimal direction of the steam flow and to get the correct speed. The de Laval designs can be included to get a higher speed and therefore reducing the steam flow. The measurements will validate if the productivity of the injector reaches the wanted level. It will also determine if water-cooling is needed and if the plunger manage to clean the orifice or if there will be coating on the edges were the plunger can not reach. It also gives a chance to determine what drop size the nozzle can handle and how well the plunger will be able to control the drop size. This can later help the control when viscosity and flow of resin changes to get the predicted drop size. Another question is how the hot steam is going to affect the resin due to viscosity and spray characterises, which also has to be further analysed?
5.3 Concept selection

The Pugh-method [21] was used to select the most promising concept to continue working with. This method is one evaluation method where the different concepts are compared by suitable requirements i.e., which are correlated to the needs, found in the needfinding phase. Table 3 shows the evaluation matrix for the concepts where the requirements is specified in the left column and are based on the project roadmap. The current resin injector is further used as reference for the other concepts to be compared with. The number of plus (i.e. better then the reference) and minus (i.e. worse then the reference) is then summarised and a weighted sum is calculated.

Table 3: Pugh matrix - Resin injector concept

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Grading</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance under production (clogging)</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Flushed under productions chances</td>
</tr>
<tr>
<td>Reliable (clogging, wear, …)</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Clogging and wears, oval orifice</td>
</tr>
<tr>
<td>Adjustable (different flow)</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Change nozzle</td>
</tr>
<tr>
<td>Atomisation (drop size)</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Approx. 1 mm</td>
</tr>
<tr>
<td>Quantity (injectors)</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>2 to 4</td>
</tr>
<tr>
<td>Manufacturing cost (injector)</td>
<td>2</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>approx. 2500 Kr</td>
</tr>
<tr>
<td>Extra cost (Resin system)</td>
<td>3</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

NR: Concept
1 Spring pressure
2 Gas atomiser
3 Duesen-schlick: Series 0/2-0/60
4 Duesen-schlick: Series 631

Table 3 shows that two concepts got the same score. However, the spring pressure (concept 1) was chosen to continue with, because of the time limit. Atomisation with steam is also a new step for Metso Panelboard and hence needed information will probably be more difficult to get. One advantage with the gas atomiser (concept 2) is the atomisation and control over drop size. However, it has not yet been proved that the drop size affects the resin consumption. As Table 3 shows, the two nozzles from Duesen-schlick did not reach the demands.
6 Detail design

In this chapter the pressure spring (concept 1) will be evaluated with final calculations and material selections. Fully drawing material to manufacture a prototype will be enclosed. Unfortunately there was no time for manufacturing a prototype and to evaluate the design by real tests.

6.1 Design

The design was based on some limited and assumed values to make the design function good and work in current resin system.

- Maximum pressure that is available form the resin system at the injector is 12 bar. This will give a maximum pressure difference of 7 bar if when the pressure in the blow line is 5 bar.
- The minimum column is assumed to be 1 mm to prevent contamination to get caught and to make manufacturing easy (since no fine tolerances then are needed).
- Plunger travel is assumed to 7 mm, consider the diaphragm (less travel as possible) and the spring (change in force).
- The resin flow is between 40 l/min and 150 l/min.

*Reinforced convoluted diaphragm*

To separate the pressure area from the spring area, a diaphragm is used. This will prevent resin leakage and prevent the cylinder from getting stuck. The material that is recommended is Viton rubber [22], which is chemical resistant, but expensive. Resin is not that toxic. Metso Panelboard uses EPDM and PTFE, which function as well. The diaphragm will take up some of the pressure in the injector, but will not stretch. Instead it will rather “roll” as shown in Figure 31.

![Figure 31: Diaphragm](image)

*Function*

The area of the annual orifice will give a pressure difference from 4 bar at 40 l/min to 7 bar at 150 l/min. The spring adjusts the annular orifice depending on the pressure in the injector. The pressure difference 4-7 bar is to prevent the plunger from oscillating. If the pressure difference is kept constant the pressure in the injector will be the same. The drop size will further be more constant when the pressure difference is larger and the flow is higher. This is because the column is larger when the flow is larger. The spring will be pre loaded to withstand the pressure from the blow line. If the blow line pressure is changed, only the preload has to be changed to get the correct equilibrium point.

*Plunger*

The angle of the plunger depends on the area difference between the largest- and lowest flow of resin as well as the distance it can move. As was stated before the largest
distance is 7 mm, and hence the angle of the plunger can be calculated. The tip is flat to prevent it from getting into the fibre flow.

6.2 Final calculations and data

The design of this resin injector is mainly based on two calculations. The first is "Bernoulli's equation" (see Equation (1)) which have been used to calculate the size of the orifice and the plunger (see Figure 32).

![Figure 32: Concept 1](image)
The second equation is used to calculate the correct spring properties. The variation in spring force

\[ \Delta F_{spring} = k \cdot \Delta x \]  \hspace{1cm} (5)

where \( k \) is the stiffness and \( \Delta x \) the variation in displacement. The pressure in the injector (\( P_2 \)) varies from 9 to 12 bar (see Figure 32) and the blow line pressure (\( P_1 \)) is 5 bar. The plunger can move between \( h_1 = 3 \) mm at the smallest flow rate \( 40 \) l/min and \( h_2 = 7 \) mm at the highest flow rate (\( 150 \) l/min). Equilibrium for the plunger gives that

\[ F_{spring} = \left( P_1 \cdot \frac{D_1}{2} \right)^2 + P_2 \cdot \frac{D_2}{2} \]  \hspace{1cm} (6)

Equation (6) for each of the two flow rates into Equation (5) then gives that

\[ F_{spring} = \frac{F_{spring_{150}} - F_{spring_{40}}}{\Delta x} \]  \hspace{1cm} (7)

where \( F_{spring_{150}} \) represents the spring force at \( 150 \) l/min and \( F_{spring_{40}} \) the spring force at \( 40 \) l/min and \( \Delta x = h_2 - h_1 \). The pre-loading distance (\( x_p \)) on the spring is calculated from equation (5) and the spring stiffness (\( k \)) to get the right force (\( F_{spring} \)) when the plunger is at it lowest point:

\[ x_p = \frac{F_{spring_{40}}}{k} - h_1 \]  \hspace{1cm} (8)

The change in drop size was predicted with Hiryasu & Katdota [15]

\[ SMD = 0.121 \cdot P_{L}^{0.131} \cdot \Delta P_{L}^{-0.135} \]  \hspace{1cm} (9)

which also shows that the effect of pressure differences increases with larger flow. In Table 4 the critical design parameters and their values are listed (see Appendix 5 for more detail calculation).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure in injector</td>
<td>9.0 to 12.0 bar*</td>
</tr>
<tr>
<td>Pressure difference</td>
<td>4.0 to 7.0 bar*</td>
</tr>
<tr>
<td>Resin flow</td>
<td>40 to 150 l/min</td>
</tr>
<tr>
<td>Column size</td>
<td>1.0 to 3.6 mm</td>
</tr>
<tr>
<td>Plunger travel</td>
<td>7 mm</td>
</tr>
<tr>
<td>Spring properties</td>
<td>( K = 38 ) N/mm ( x_p = 11 ) mm pre-loading distance</td>
</tr>
<tr>
<td>Spring force</td>
<td>523 to 685 N</td>
</tr>
<tr>
<td>Drop size [MMD]</td>
<td>203 to 223 ( \mu m )*</td>
</tr>
</tbody>
</table>

*Blow line pressure 5 bar,**Only the change is interesting
Equation (5) - (9) does not hold below 40 l/min since the column will become too small. However, it has been ensured that when there is no pressure in the injector, the pre load force is high enough to keep the plunger in closed position (see Appendix 5).
6.3 Exploded view and list of components

![Figure 33: Pressure Spring (exploded view)](image)

<table>
<thead>
<tr>
<th>Article</th>
<th>Name</th>
<th>Quantity</th>
<th>Purchased parts</th>
<th>Manufactured parts</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Compressor plate</td>
<td>1</td>
<td>M</td>
<td></td>
<td>EN 1.4301</td>
</tr>
<tr>
<td>3</td>
<td>Cylinder</td>
<td>1</td>
<td>M</td>
<td></td>
<td>SS 5640-15</td>
</tr>
<tr>
<td>4</td>
<td>Hexagon screw (M6)</td>
<td>4</td>
<td>x</td>
<td></td>
<td>ISO 4017</td>
</tr>
<tr>
<td>5</td>
<td>Hexagon nut (M6)</td>
<td>3</td>
<td>x</td>
<td></td>
<td>ISO 4032</td>
</tr>
<tr>
<td>6</td>
<td>Injector house lower</td>
<td>1</td>
<td>M</td>
<td></td>
<td>EN 1.4301</td>
</tr>
<tr>
<td>7</td>
<td>Injector house upper</td>
<td>1</td>
<td>M</td>
<td></td>
<td>EN 1.4301</td>
</tr>
<tr>
<td>8</td>
<td>Lid</td>
<td>1</td>
<td>M</td>
<td></td>
<td>EN 1.4301</td>
</tr>
<tr>
<td>9</td>
<td>Needle</td>
<td>1</td>
<td>M</td>
<td></td>
<td>EN 1.4301</td>
</tr>
<tr>
<td>10</td>
<td>Restriction plate</td>
<td>1</td>
<td>M</td>
<td></td>
<td>EN 1.4301</td>
</tr>
<tr>
<td>12</td>
<td>Slider</td>
<td>1</td>
<td>M</td>
<td></td>
<td>5640-15</td>
</tr>
<tr>
<td>13</td>
<td>Threaded shaft (M6)</td>
<td>1</td>
<td>x</td>
<td></td>
<td>EN 1.4301 8.8</td>
</tr>
<tr>
<td>14</td>
<td>Washer</td>
<td>4</td>
<td>x</td>
<td></td>
<td>FE/ZN D6</td>
</tr>
<tr>
<td>15</td>
<td>Spring</td>
<td>1</td>
<td>x</td>
<td></td>
<td>SS 1774</td>
</tr>
<tr>
<td>16</td>
<td>Oring</td>
<td>1</td>
<td>x</td>
<td></td>
<td>Viton</td>
</tr>
<tr>
<td>17</td>
<td>Diaphragm</td>
<td>1</td>
<td>x</td>
<td></td>
<td>EPDM</td>
</tr>
</tbody>
</table>

**Total No. parts** 23
6.4 Technical data

In Table 6 the technical data for the pressurised spring solution is presented.

Table 6: Technical data for the resin injector

<table>
<thead>
<tr>
<th>Subject</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (∅ x L)</td>
<td>102 mm x 158 mm</td>
</tr>
<tr>
<td>No. parts</td>
<td>23</td>
</tr>
<tr>
<td>No. articles</td>
<td>15</td>
</tr>
<tr>
<td>Weight</td>
<td>≈ 2 kg</td>
</tr>
<tr>
<td>Resin flow</td>
<td>40 to 150 l/min</td>
</tr>
<tr>
<td>Pressure difference</td>
<td>4 to 7 bar if the blow line pressure is 5 bar</td>
</tr>
<tr>
<td>Drop size [MMD]</td>
<td>203 to 223 μm*</td>
</tr>
<tr>
<td>Manufacturing cost</td>
<td>7000 SEK</td>
</tr>
</tbody>
</table>

*Only the change is interesting

Figure 34: Resin injector fixed on the blow line at 45° angle with the flow
6.5 Further work

The next step in this project would be to manufacture a prototype, and thereby ensure the function in reality. The test can be performed with water but the only way of validate the functionality is it to use resin with the correct density and viscosity. The diaphragm should also be evaluated in the test with rapid flow changes under a long time to prove its function. The mechanical wear in the injector should also be evaluated to see if the materials shall be changed etc. The drop size and spray effect is another property that should be tested in a controlled environment so that objective conclusion can be drawn.

Decreasing the minimum column will also result in a decrease of the column at the largest flow. This can be achieved by increasing the orifice diameter. Hence, since the injector is mostly running at 100 % the optimisation shall be concentrated there, without aggravating the functionality. The pressure in the injector is restricted to 16 bar. If there is possible to get a larger pressure at the largest flow, the change in drop size will be even smaller.

“Bullet proof” production is when maintenance can be performed on the injector while in production. This can be achieved by using two resin injectors who can be switched when there is time for service or the nozzle has clogged. Water-cooling is necessary to keep the nozzle that is not running cooled. One problem is to remove the clogged nozzle when there still is pressure in the blow line.
7 Discussion

The result of this master’s thesis project is a new resin injector design with the ability to keep the drop size constant regardless of the resin flow. The plunger suspended by a spring automatically adjusts the orifice to get the correct pressure difference and thereby flow rate. The plunger will also work as an extra cleaning feature, which is a benefit, compared to the current solution.

The technique of keeping the pressure difference is successfully used in pressure regulators. Hence, the technique works but has not yet been implemented in a resin nozzle. Because of the lack of information and reports in this subject the design could not be connected directly to the resin consumption issue. The developed product is however a more mechanical advanced and probably more reliable design with the cleaning function, compared to today’s design. A prototype has to be manufactured so that the function and the effect of the new resin injector (pressure spring) can be evaluated. Most likely there will not be any visible change in resin consumption compared to current nozzles, i.e. the change will not be measurable with today’s evaluation methods.

Resin consumption is a big issue in the MDF process and the problem is to evaluate changes in the process. Further research is needed to gain knowledge regarding how to reduce the amount of resin. This issue can be addressed in different ways. The whole process from raw material to the press and how that affects the resin consumption should be studied. This has to be done to be able to optimise different plants and their production. With large difference in climate, raw material and more, every factory is unique. The resin consumption could also be studied from a smaller scope. The study could for instance be restricted to the blow line. Then a more narrow investigation on the fibre and the resin distribution, to optimise the blow line and resin injector system could be performed. The fact that the resin penetrates into the fibres is proved, but the effects of that are still unknown. Many theories suggests that the resin shall be distributed with fibre to fibre collision, the resin should be on the fibre. Another theory states that the resin is destroyed or “pre cured“ before it reaches the press. Another problem is how to evaluate any changes in the process. There is no good way of investigating resin consumption, resin converge or distribution such that small changes can be tracked. The problem with today’s methodologies is that the general aspects are concealed since the scope is too small. The findings must connect to the process and the result of a change in design must be possible to trace in terms of the final product. In chapter 3.1 the resin blending guidelines show more of the key issues regarding resin consumption.
8 References


[8] D. Robson, What happens with blending in the MDF blow line, University of Wales (Bangor, Gwynedd, Wales) - 1991


[16] Dysor och arematur för vätskespridning, katalog 55, Spraying systems Co, 2006


9 Appendix

Appendix 1 – Diagram VeeJet drop size vs. resin pressure

The flowing figure is based on water and spray in quiescent air. The x-label is pressure difference (psi) and y-label is drop size (μm).

Figure 1: Drop size for VeeJet, 1 psi = 0.06895 bar
Appendix 2 – Drop size in blow line simulation

This simulation on the impact of drop size in high speed blow line. The simulation was performed as follow with a singe nozzle and a fibre free blow line assuming that:

- Turbulent dispersion of water droplets is accounted for Particle drag model, Schiller-Naumann.

Blow line:
- Straight pipe (blow line) with steam flow
- Steam velocity = 60 m/s
- Steam density = 3.2 kg/m³
- Only steam in blow line (no fibres)
- Pipe diameter = 125 mm

Nozzle:
- Monodisperse (single diameter) water droplets injected with velocity 34 m/s.
- Two nozzle angles were tested
  - Nozzle perpendicular to steam flow
  - Nozzle 45° along the flow
- Nozzle cone angle = 80° (2x40°, circular cone)
- Three different droplet diameters, 1 mm, 200 μm and 50 μm
- Mass flow of water droplets = 0.6667 kg/s

Figure 2: Simulation injector angle 0°
Results and discussion:

- Large droplets can reach the opposite wall in the blow line if they do not collide with fibres.
- Low concentration of fibres => droplets can hit opposite wall. Could occur when fibre flow variations are large.
- Droplets as small as 50 microns are not likely to hit the opposite wall.
- The particle bounces when they hit the wall in stimulation, which is not likely to happen with resin in a blow line. The resin should just stick to the wall.
Appendix 3 – Calculations for the steam atomiser

The calculation in this Table 1 shows the used input and variation in flow from Case 1 to 4, with the Equation (1-4) to predict the drop size. This was the ground for the design on the Concept 2 – Steam atomiser.

Definition of droplet size:

Two expressions are used for defining "average" droplet size or "mean" size:

"SMD" is Sauter mean diameter and "MMD" which is the drop diameter corresponding to the 50% point of the cumulative mass distribution curve.

\[
SMD = \frac{\text{SnD}3}{\text{SnD}2}.
\]

It is found that that:

\[
\frac{\text{MMD}}{\text{SMD}} = 1.20, \text{ Within +/-5%} \quad (A3-1)
\]
Table 1: Drop size calculation with steam atomisation, Equation (2-3)

<table>
<thead>
<tr>
<th>Case no</th>
<th>Input = red</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. txt.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Input liquid:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature $T_L$ (°C)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Density $ρ_L$ (kg/m³)</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
</tr>
<tr>
<td>Dyn. viscosity $μ_L$ (kg/m.s or N s/m²)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Surf. tension $σ_L$ (N/m or kg/s)</td>
<td>6.00E-02</td>
<td>6.00E-02</td>
<td>6.00E-02</td>
<td>6.00E-02</td>
</tr>
<tr>
<td>Annular orifice area $A_L$ (m²)</td>
<td>7.23E-05</td>
<td>7.23E-05</td>
<td>7.23E-05</td>
<td>7.23E-05</td>
</tr>
<tr>
<td>Liq. vol flow $Q_L$ (l/min)</td>
<td>150.00</td>
<td>100.00</td>
<td>60.00</td>
<td>40.00</td>
</tr>
<tr>
<td>Liq. mass flow $W_L$ (kg/s)</td>
<td>2.975</td>
<td>1.983</td>
<td>1.190</td>
<td>0.793</td>
</tr>
</tbody>
</table>

**Input air:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature $T_A$ (°C)</td>
<td>160@5bar</td>
<td>160@5bar</td>
<td>160@5bar</td>
<td>160@5bar</td>
</tr>
<tr>
<td>Density $ρ_A$ (kg/m³)</td>
<td>3.17</td>
<td>3.17</td>
<td>3.17</td>
<td>3.17</td>
</tr>
<tr>
<td>Dyn. viscosity $μ_A$ (kg/m.s or N s/m²)</td>
<td>2.00E-04</td>
<td>2.00E-04</td>
<td>2.00E-04</td>
<td>2.00E-04</td>
</tr>
<tr>
<td>Annular orifice area $A_A$ (m²)</td>
<td>1.58E-04</td>
<td>1.58E-04</td>
<td>1.58E-04</td>
<td>1.58E-04</td>
</tr>
<tr>
<td>Mass flow $W_A$ (kg/s)</td>
<td>1.49E-01</td>
<td>1.49E-01</td>
<td>1.49E-01</td>
<td>1.49E-01</td>
</tr>
</tbody>
</table>

| $W_A/W_L$                  | 0.05   | 0.08   | 0.13   | 0.19   |

**Velocity:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air velocity $U_A$ (m/s)</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Liquid velocity $U_L$ (m/s)</td>
<td>35</td>
<td>23</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Rel. velocity $U_R$ (m/s)</td>
<td>265</td>
<td>277</td>
<td>286</td>
<td>291</td>
</tr>
</tbody>
</table>

**Nozzle data:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefilm. Lip diam. $D_p$ (m)</td>
<td>0.022</td>
<td>0.022</td>
<td>0.022</td>
<td>0.022</td>
</tr>
</tbody>
</table>

**Result for prefilming steam atomizer acc. to El-Shanawany & Lefebvre:**

| Sauter Mean diam. $SMD$ (m) | 6.49E-05 | 4.42E-05 | 2.78E-05 | 1.95E-05 |
| SMD (μm)                    | 64.9     | 44.2     | 27.8     | 19.5     |
| Mass mean diam. $MMD$ (μm)  | 77.9     | 53.1     | 33.3     | 23.5     |

**Result for single convergent steam atomizer acc. to Kim & Marshall**

| Mass mean diam. $MMD$ (m) | 1.75E-04 | 1.14E-04 | 6.77E-05 | 4.51E-05 |
| MMD (μm)                  | 175      | 114      | 68       | 45       |
| Sauter mean diam. $SMD$ (m) | 146    | 95       | 56       | 38       |
This Table 3 calculates gas flow through a nozzle in the subcritical and overcritical flow regime for ideal gases.

### Table 2: Saint-Venant, Wantzel variables explanation

<table>
<thead>
<tr>
<th>Name</th>
<th>Label</th>
<th>Extra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas constant</td>
<td>R</td>
<td>287 for air, and 462 for steam</td>
</tr>
<tr>
<td>Gas constant (= Cp/Cv)</td>
<td>κ</td>
<td>air=1.4 or 1.135 for sat. steam or 1.3 for SH steam</td>
</tr>
<tr>
<td>Mass flow</td>
<td>W</td>
<td>Kg/s</td>
</tr>
<tr>
<td>Contraction coefficient</td>
<td>μ</td>
<td>0.62 for sharp edged holes 0.95-0.98 for rounded holes</td>
</tr>
<tr>
<td>Hole area</td>
<td>A</td>
<td>m²</td>
</tr>
<tr>
<td>Expansion coefficient</td>
<td>Psi</td>
<td></td>
</tr>
<tr>
<td>Static pressure before opening</td>
<td>P₁</td>
<td>Pa abs</td>
</tr>
<tr>
<td>Static pressure after opening</td>
<td>P₂</td>
<td></td>
</tr>
<tr>
<td>Temp. of gas before</td>
<td>t₁</td>
<td>°C</td>
</tr>
<tr>
<td>Abs. temp. of gas before opening</td>
<td>T₁</td>
<td>°K</td>
</tr>
</tbody>
</table>

### Formulas: (Saint-Venant and Wantzel)

\[ W = \mu \cdot A \cdot P₁ \cdot \Psi \cdot \left( \frac{2}{T \cdot R} \right) ; \text{kg/s} \quad (A3-2) \]

\[ \Psi = \left( \frac{\kappa}{(\kappa - 1)} \right) \left( \frac{P₂}{P₁} \right)^{2 \kappa} \left( \frac{P₂}{P₁} \right)^{(\kappa+1)/\kappa} ; \text{for subcritical flow} \quad (A3-3) \]

\[ \Psi = \left( \frac{\kappa}{(\kappa - 1)} \right) \left( \frac{P₂}{P₁} \right)^{2 \kappa} \left( \frac{P_k}{P₁} \right)^{(\kappa+1)/\kappa} ; \text{for overcritical flow} \quad (A3-4) \]

\[ Ra₂ = Ra₁ \cdot \left( \frac{P₂}{P₁} \right)^{1/\kappa} ; \text{kg/m}^3 \quad (A3-5) \]

\[ Ra₂ = Ra₁ \cdot \left( \frac{P_k}{P₁} \right)^{1/\kappa} ; \text{kg/m}^3 \quad (A3-6) \]

\[ \frac{P_k}{P₁} = \left( \frac{2}{\kappa + 1} \right)^{\kappa/(\kappa-1)} \text{; where Pk is critical pressure} \quad (A3-7) \]
The Table 3 shows what the orifice area (A) should be with steam, at the different pressure difference (P1-P2) and the target speed 300 m/s (U).

Table 3: Calculates gas flow through a nozzle, Saint-Venant and Wantzel, Equation (A3-2 to A3-7).

<table>
<thead>
<tr>
<th>Case</th>
<th>Input data</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>J/kg,°C</td>
<td>462</td>
<td>462</td>
<td>462</td>
<td>462</td>
</tr>
<tr>
<td>κ</td>
<td></td>
<td>1.3</td>
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<tr>
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<td>A</td>
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<td>1.58E-04</td>
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<td>D</td>
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<td>P1</td>
<td>Pa abs</td>
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<td>1.00E+06</td>
<td>1.00E+06</td>
<td>1.00E+06</td>
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<tr>
<td>P2</td>
<td>Pa abs</td>
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<td>4.00E+05</td>
<td>5.00E+05</td>
<td>6.00E+05</td>
</tr>
<tr>
<td>P2/P1</td>
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<td>0.30</td>
<td>0.40</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>Pk/P1</td>
<td>Overcritical</td>
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<td>0.55</td>
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</tr>
<tr>
<td>Psi</td>
<td>Subcritical</td>
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<td>0.4718</td>
<td>0.4718</td>
<td>0.4686</td>
</tr>
<tr>
<td>t1</td>
<td>°C</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>T1</td>
<td>°K</td>
<td>433</td>
<td>433</td>
<td>433</td>
<td>433</td>
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<tr>
<td>W</td>
<td>kg/s</td>
<td>1.49E-01</td>
<td>1.49E-01</td>
<td>1.49E-01</td>
<td>1.49E-01</td>
</tr>
<tr>
<td></td>
<td>kg/h</td>
<td>536.4</td>
<td>536.4</td>
<td>536.4</td>
<td>536.4</td>
</tr>
<tr>
<td>Ra1</td>
<td>kg/m³</td>
<td>4.999</td>
<td>4.999</td>
<td>4.999</td>
<td>4.999</td>
</tr>
<tr>
<td>Ra2</td>
<td>kg/m³</td>
<td>not relev.</td>
<td>not relev.</td>
<td>not relev.</td>
<td>3.375</td>
</tr>
<tr>
<td>Rak</td>
<td>kg/m³</td>
<td>3.137</td>
<td>3.137</td>
<td>3.137</td>
<td>not relev.</td>
</tr>
<tr>
<td>Q(=V2 or Vk)</td>
<td>m³/s</td>
<td>4.75E-02</td>
<td>4.75E-02</td>
<td>4.75E-02</td>
<td>4.42E-02</td>
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<tr>
<td></td>
<td>m³/min</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>m³/h</td>
<td>171.0</td>
<td>171.0</td>
<td>171.0</td>
<td>159.0</td>
</tr>
<tr>
<td>U (=U2 or Uk)</td>
<td>m/s</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>279</td>
</tr>
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</table>
Appendix 4 – Simulation on pressure difference

Equation (1) that was used to calculate the correct pressure difference. The flow friction coefficient ($\mu$) was set to 0.62 because of a sharp orifice. It is not suited for an annular orifice, but the equation was evaluated with one special case computational fluid dynamic (CFD) simulation with the software CFX. This showed that the approximated calculation of the area gave almost correct answer, with the flow friction coefficient ($\mu$) set to 0.62. Figure 4 shows a 3,6 bar pressure difference but the simulation nozzle had a slightly larger gap then the calculation model.

**EXPRESSIONS:**

- $\text{inletvel} = \frac{(20 \times 10^{-3}/60) \, [m^3 \, s^{-1}]}{(\pi*(24 \times 10^{-3} \, [m])^2/8)} \Rightarrow 40 \, l/min$
- **MATERIAL:** resin
- **DYNAMIC VISCOSITY:**
  - Dynamic Viscosity $= 100 \times 10^{-3} \, [Pa \, s]$
  - Density $= 1190 \, [kg \, m^{-3}]$
  - Molar Mass $= 1.0 \, [kg \, kmol^{-1}]$
- **BOUNDARY:** inlet
  - Boundary Type = INLET
  - Location = inlet
- **BOUNDARY CONDITIONS:**
  - **FLOW REGIME:**
    - Option = Subsonic
  - **MASS AND MOMENTUM:**
    - Normal Speed = inletvel
  - **BOUNDARY:** outlet
    - Boundary Type = OPENING
    - Location = outlet
- **BOUNDARY CONDITIONS:**
  - **FLOW DIRECTION:**
    - Option = Normal to Boundary Condition
  - **FLOW REGIME:**
    - Option = Subsonic
  - **MASS AND MOMENTUM:**
    - Option = Opening Pressure and Direction
    - Relative Pressure = 0 \, [Pa]
  - **TURBULENCE MODEL:**
    - Option = Laminar
  - **SIMULATION TYPE:**
    - Option = Steady State
- **CONVERGENCE CONTROL:**
  - Length Scale Option = Conservative
  - Maximum Number of Iterations = 1000
  - Timescale Control = Auto Timescale
- **CONVERGENCE CRITERIA:**
  - Conservation Target = 0.01
  - Residual Target = 0.00001

8(15)
Figure 4: Pressure, Pa

Figure 5: Velocity, m/s
Appendix 5 – Calculation pressure spring

Area calculation for getting the correct pressure difference in an annular orifice, is Equation (1) used.

Table 4: Bernoullis, resin flow and pressure difference changed between the cases 1 to 7, Equation (1).

<table>
<thead>
<tr>
<th>Red = Input</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case no:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure difference ΔP N/m²</td>
<td>4.00E+05</td>
<td>4.50E+05</td>
<td>5.00E+05</td>
<td>5.50E+05</td>
<td>6.00E+05</td>
<td>6.50E+05</td>
<td>7.00E+05</td>
</tr>
<tr>
<td>Density ρ kg/m³</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
<td>1190</td>
</tr>
<tr>
<td>Flow Q m³/s</td>
<td>6.67E-04</td>
<td>9.72E-04</td>
<td>1.28E-03</td>
<td>1.58E-03</td>
<td>1.88E-03</td>
<td>2.20E-03</td>
<td>2.50E-03</td>
</tr>
<tr>
<td>Friction coefficient μ</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>Area orifice A m²</td>
<td>4.15E-05</td>
<td>5.70E-05</td>
<td>7.11E-05</td>
<td>8.40E-05</td>
<td>9.57E-05</td>
<td>1.07E-04</td>
<td>1.18E-04</td>
</tr>
<tr>
<td>Annular orifice area A m²</td>
<td>4.15E-05</td>
<td>5.70E-05</td>
<td>7.11E-05</td>
<td>8.40E-05</td>
<td>9.57E-05</td>
<td>1.07E-04</td>
<td>1.18E-04</td>
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<tr>
<td>Radius orifice r O m</td>
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<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
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<tr>
<td>Radie plunger r m</td>
<td>0.0060</td>
<td>0.0056</td>
<td>0.0051</td>
<td>0.0047</td>
<td>0.0043</td>
<td>0.0039</td>
<td>0.0034</td>
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<tr>
<td>Area injector A₁ m²</td>
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<td>5.07E-04</td>
<td>5.07E-04</td>
<td>5.07E-04</td>
<td>5.07E-04</td>
<td>5.07E-04</td>
<td>5.07E-04</td>
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<tr>
<td>Injector pressure P₁ Pa</td>
<td>9.00E+05</td>
<td>9.50E+05</td>
<td>1.00E+06</td>
<td>1.05E+06</td>
<td>1.10E+06</td>
<td>1.15E+06</td>
<td>1.20E+06</td>
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<tr>
<td>Force injector F₁ N</td>
<td>455.92</td>
<td>481.25</td>
<td>506.58</td>
<td>531.91</td>
<td>557.24</td>
<td>582.57</td>
<td>607.90</td>
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<tr>
<td>Pressure area blow line A₂ m²</td>
<td>1.54E-04</td>
<td>1.54E-04</td>
<td>1.54E-04</td>
<td>1.54E-04</td>
<td>1.54E-04</td>
<td>1.54E-04</td>
<td>1.54E-04</td>
</tr>
<tr>
<td>Blow line pressure P₂ Pa</td>
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<td>5.00E+05</td>
<td>5.00E+05</td>
<td>5.00E+05</td>
<td>5.00E+05</td>
<td>5.00E+05</td>
<td>5.00E+05</td>
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<tr>
<td>Force plunger F₂ N</td>
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<td>76.97</td>
<td>76.97</td>
<td>76.97</td>
<td>76.97</td>
<td>76.97</td>
<td>76.97</td>
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<tr>
<td>Spring force Fₘ N</td>
<td>532.89</td>
<td>558.22</td>
<td>583.55</td>
<td>608.88</td>
<td>634.21</td>
<td>659.54</td>
<td>684.87</td>
</tr>
<tr>
<td>Plunger travet h mm</td>
<td>3.0</td>
<td>3.7</td>
<td>4.3</td>
<td>5.0</td>
<td>5.7</td>
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The Equation (5-8) is used in Table 5 to calculate the spring properties.

Table 5: Spring properties, injector pressure and plunger travle is chaced between the cases 1 to 7.

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<tr>
<th>Red = Input</th>
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<th>2</th>
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<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<td>Case no:</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>0.0145</td>
<td>0.0145</td>
<td>0.0145</td>
<td>0.0145</td>
<td>0.0145</td>
<td>0.0145</td>
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<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
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<td>5.07E-04</td>
<td>5.07E-04</td>
<td>5.07E-04</td>
<td>5.07E-04</td>
<td>5.07E-04</td>
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</tr>
<tr>
<td>Injector pressure P₁ Pa</td>
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<td>9.50E+05</td>
<td>1.00E+06</td>
<td>1.05E+06</td>
<td>1.10E+06</td>
<td>1.15E+06</td>
<td>1.20E+06</td>
</tr>
<tr>
<td>Force injector F₁ N</td>
<td>455.92</td>
<td>481.25</td>
<td>506.58</td>
<td>531.91</td>
<td>557.24</td>
<td>582.57</td>
<td>607.90</td>
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<tr>
<td>Pressure area blow line A₂ m²</td>
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<td>1.54E-04</td>
<td>1.54E-04</td>
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<tr>
<td>Force plunger F₂ N</td>
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<td>76.97</td>
<td>76.97</td>
<td>76.97</td>
<td>76.97</td>
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<tr>
<td>Spring force Fₘ N</td>
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<td>558.22</td>
<td>583.55</td>
<td>608.88</td>
<td>634.21</td>
<td>659.54</td>
<td>684.87</td>
</tr>
<tr>
<td>Plunger travet h mm</td>
<td>3.0</td>
<td>3.7</td>
<td>4.3</td>
<td>5.0</td>
<td>5.7</td>
<td>6.3</td>
<td>7.0</td>
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</tbody>
</table>

The Equation (5-8) is used in Table 5 to calculate the spring properties.
The flowing Equation (9) by Hiryasu & Katdota is used to approximate the drop size change in Table 6.

Table 6: Drop size change, the pressure difference and flow is changed between the cases 1 to 7.

<table>
<thead>
<tr>
<th>Red = Input</th>
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<th></th>
<th></th>
<th></th>
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<td>6</td>
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<tr>
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<td>3.17E+00</td>
<td>3.17E+00</td>
<td>3.17E+00</td>
<td>3.17E+00</td>
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<td>Q_L</td>
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<td>9.72E+05</td>
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<td>1.58E+06</td>
<td>1.88E+06</td>
</tr>
<tr>
<td>Pressure difference</td>
<td>P_L</td>
<td>4.00E-01</td>
<td>4.50E-01</td>
<td>5.00E-01</td>
<td>5.50E-01</td>
<td>6.00E-01</td>
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<td>Sauter Mean Diameter</td>
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<td>178</td>
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<td>183</td>
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<tr>
<td>Mass Median Diameter</td>
<td>MMD</td>
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<td>214</td>
<td>217</td>
<td>220</td>
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</tbody>
</table>
Appendix 6 – Spray Nozzles test BLW

The main activity in this investigation is to test spraying equipment (spray nozzle) in the blow line, close to the blow valve. Addition of UF resin (10%) with two different solid content (whit concentration 40% and approximately 60%). Water was added separately to compensate for the water diluted of the low solid content UF resin (40%) and to have the same setup on the dryer. A repetition of the first Trial (BLW01) was performed (BLW04) to make sure that the tests are reliable. A variation of the resin distribution on fibres was expected due to the different flow/pressure in the resin spraying equipment. Production rate of fibres was set to 60 kg/h. The test was carried out at Metso Panelboard pilot-plant (research center) which is a scaled MDF process plant. The process was further kept at constant production.

<table>
<thead>
<tr>
<th>Parameters (target) Unit</th>
<th>BLW01</th>
<th>BLW02</th>
<th>BLW03</th>
<th>BLW04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive 1/Resin</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Content (wb) %</td>
<td>40</td>
<td>60</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Resin/Fibre(db/db) %</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Special Activity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spry Nozzle Orifice mm</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Water addition %</td>
<td>2</td>
<td>12</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. of Panels</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Raw Material

Additive 1 Type of Additive

Name: UFResin (Conventional MDFresin)
Injection Position: Blow line just after the Blow valve
Addition Resin/Fibre(db/db) %: 10

Additive 2 Type of Additive

Name: Ammonium Chloride
Addition of Add./Resin(db/db) %: 1

Additive 3 Type of Additive

Name: Hexamine
Addition of Add./Resin(db/db) %: 0.2

Wax

Name: Wax
Addition Wax/Fibre(db/db) %: 1.0

Defibration Process Data Unit

Type of Defibrator: OVP20
Segment: 5447

Defibrator house Unit

Pressure bar: 8
Temperature °C: 170

Main Motor + Defibrator Unit

Speed rpm: 1500
Specific energy Maximum kWh/t: 160
Production rate kg/h: 60

Fibre & Panels Unit

Core Density kg/m³: 650
Surface Density kg/m³: 1000
Average Density kg/m³: 750
Depth of Density mm: 2.00
MC fibre db %: 8
Dry Content fibre (wb) %: 92.6
Thickness mm: 12.0
Side A mm: 500
Side B mm: 600
Weight(db)/panel kg: 2.700
Weight(wb)/panel (+3%) kg: 3.003

Panel Production & Pressing Unit

No. of Panels: 28
Weight(db)/panel kg: 2.700
Plate Temperature °C: 190
Press factor s/mm: 10
Pressing Time s: 120
Result

After the boards were pressed and test pieces were cut to the right size, four test were preformed; resin quantity with Kjeldahl method on the fibres, density profile, internal bond (IB) and thickness swelling over the average density on the board. In Figure 40 the IB is shown and the 4 test runs. The tests runs are labeled with resin quantity (RC), resin concentration and if extra were water were added (W+). In Figure 41 the thickness swelling test is shown.

![Blowline BLW1-5](image)

**Figure 6: Internal bond**
Discussion

The test gave quality boards and no production stops did occur. The only thing that did not hit the target was the resin quantity, which differs between the tests. The first run had 0.5% less the the target 10%, the 2:a and 3:e had more then 2% to munch and the 4:th had 1% to much (see figure and RC). This makes the result more difficult to evaluate but with the density and resin content the relation is pretty much linear, so the curves can be compared with each other. Figure 40 shows that there is no change in IB between the test run if the resin change is neglected. However the thickness swelling is much the same with may give the thought that the resin with the lower viscosity has a better resistance to water. Because larger quantity of resin gives better thickness swelling and the test run BLW01 and BLW04 has less resin quantity but gives the same result as BLW02-03. This can be a result of larger penetration of resin and makes less chance for water to penetrate into the fibre.

Drawing conclusions from the test is difficult because of the relative small changes in the test runs and with the variation in the process. The largest variation in the board is the density because of the variation in the forming stage and the hot press. The forming is preformed by hand and dose not give an even mat and pre press. The hot press has also large variation because the boards is pressed one after each other so the temperature is difficult to keep the same and will give an uneven curing. The fact that the process is approx. 50 times smaller then a normal factory gives another problem when comparing it to the real process. The result of the test shows that is difficult to se changes in the board properties, with changing the nozzle and pressure difference in the nozzle. Maybe at a real factory were the variations in the forming stage and hot press is less, the nozzles can be evaluated.
Another thing at the pilot plant is that it produces really good boards with 10% resin and maybe can not give a better result. So the test should be done in a less perfect production.