The Institute of Materials, Minerals and Mining
Achieving Profile & Flatness in Flat Products
24 – 25 January 2006, Austin Court, Birmingham, UK

Flatness and profile the problems that can exist in the design of the spray actuators – David Tucker, Lechler Ltd., Sheffield, UK

Introduction

Flatness or shape control is one of the primary factors by which the quality of strip is measured; attention must therefore be paid to the work roll temperature and internal temperature distribution if acceptable quality is to be achieved. Many actuators are available to assist the plant in achieving the targeted quality, including, roll bending, side shift, inflatable and segmented back-up rolls to name a few. The use of roll cooling systems as one of the main actuators is well known. Therefore what will be described in this paper is Lechler's experience of the header design, including the flow in coolant chambers, valves and nozzles. It will also comment upon the use of simulation software and the optimisation of the spray patterns to ensure that the maximum heat is taken from the work roll.
As described by Ishikawa(1) et al, the major factors, which determine the capability of the roll cooling system to affect the profile or shape, are:

1. Pressure-flow characteristics of the spray nozzles
2. Nozzle layout arrangement
3. Temperature differential between roll and coolant
4. Oil concentration of the coolant (or rolling oil used)
5. Roll diameter
6. Roll speed.

Hot or Cold rolling mills use large amounts of energy that, during the process of rolling, are converted into heat and this heat is a source of control problems. Characteristically, a rolling mill consists of a pair of small diameter work roll, in contact with the material to be rolled and either larger backup roll or intermediate rolls between the back-up and work roll. These rolls are used to squeeze the material to reduce its thickness, in doing so large amounts of energy are used to achieve the desired thickness reduction.

The mill operator is charged with fighting this induced heat, which leads to symmetrical and asymmetrical expansion of the work rolls. Of these, symmetrical expansion is the easier (non-uniform thermal expansion across the work roll, is referred to as thermal camber) to develop solutions for and the earlier mentioned actuators are very successful in the majority in solving these problems.

The asymmetrical deviations can be the more complex variable to deal with, since they can occur anywhere on the work roll and take the form of isolated pockets of thermal expansion. The problem of keeping the roll surface flat is called shape control.

A roll-cooling header contains a number of cooling spray nozzles located parallel to the roll, and for this paper we will assume that a valve controls the flow through each spray nozzle. The coolant is sprayed onto the work roll surface reducing the localized thermal expansion. The cooling effect of a spray arrangement is not purely derived from the impact area of the sprays. The parameters, which influence the cooling effect, include:

The spray impingement area; In general it is better for the pattern to occupy as large an area as possible, even though this reduces the coolant flow per unit area. As a result of this the net cooling is increased, as is the degree of control of the cooling via spray nozzle switching. Large area generally equals a large circumferential distance, since each nozzle needs to be reasonably confined to its own axial zone to allow good control of flatness.

Type of nozzle, cone or flat; Cone sprays tend to give a more uniform spray pattern and thus tend to give a higher Cooling Effect for the same total flow. However, it is possible to obtain equivalent effects from flat sprays, but this usually requires a larger circumferential distance on the roll surface. Whereas flat jets are often preferred as they are simpler and cheaper than cones and in addition are thought to be less prone to blockage. It is also easier to avoid striping of strip with flat jets because their patterns can be made to overlap axially, whereas those of cone sprays ‘clash’ and produce a ridge of coolant. However, the twist angle of flat jets needs to be set and monitored otherwise very irregular cooling patterns can be produced. Cone sprays have the advantage of being axi-symmetric and no setting is required.

Interaction between banks; when spray banks are placed close to each other on the roll surface, then the net effect of the two is generally less than the sum of their separate effects. This is because both share some portion of the roll surface, even if not directly under the spray.

The interesting thing about sprays is that each nozzle affects a large section of the roll. The designer will therefore focus the sprays to give an intense effect at a selected point. But the effects are not just felt at the point of focus they encompass the section directly beneath it also. This leads to an interactive

Multiple Input multiple output (MIMO) system, rather than a series of de-coupled single input single output (SISO) systems.

Roll cooling system design model.

Every roll cooling system manufacturer will have some kind of operational procedures model, which is used to handle the project from first contact enquiry to order. Figure 1 shows the Lechler procedure and flow diagram for handling the "first contact" stage. For this paper this will not be developed further.

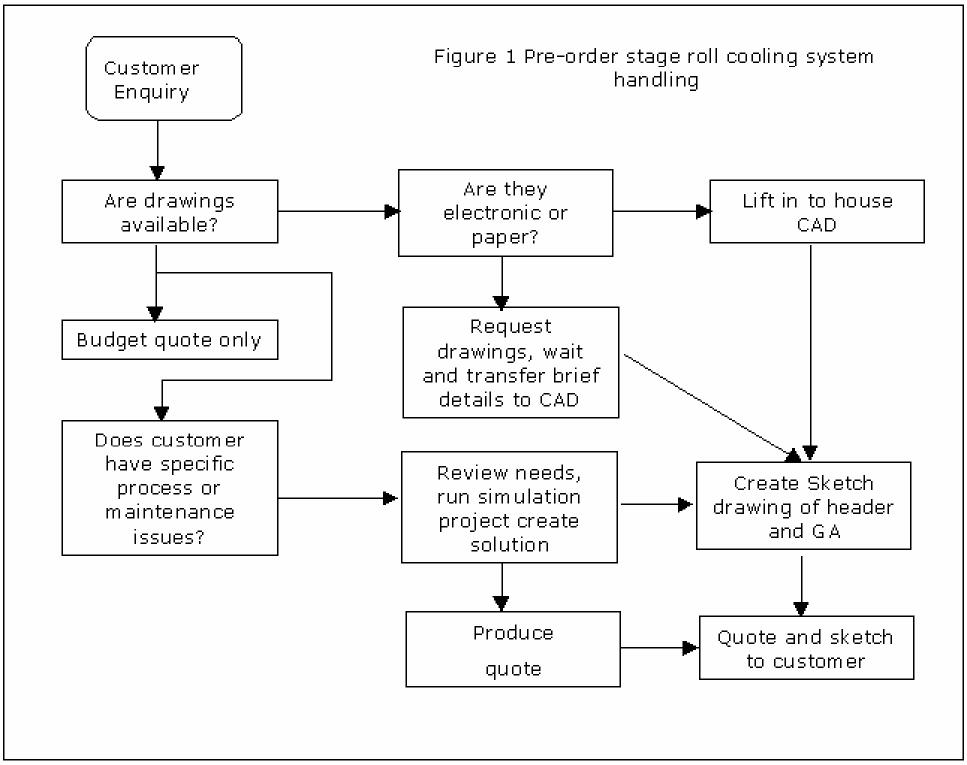


Figure 1 Pre-order stage roll cooling system handling

The detailed engineering of the system will commence at the order stage, although pre-work will have taken place. This pre-work may have been as detailed as providing General arrangement (GA) drawings of headers placed in the customers mill and solving some of the issues of working around mill furniture. It may also have included work to review the processes existing thermal capabilities against the new headers in the form of a simulation of the heat extraction capabilities.

Figure 2 shows the flow of a project once an order is received. This paper will not cover the manufacturing process or some of the validation that is required at various stages of the process.

It will focus on the following stages that are fundamental to the successful development of a roll cooling system.

1. Spray pattern development
2. Spray positioning
3. Pressure drop in headers
4. Coolant velocity in pipes and headers
5. Turbulence in headers
6. Design integrity

The first five points will be used in developing a correlation with heat extraction from the work rolls and the latter that the headers will be fit for purpose.

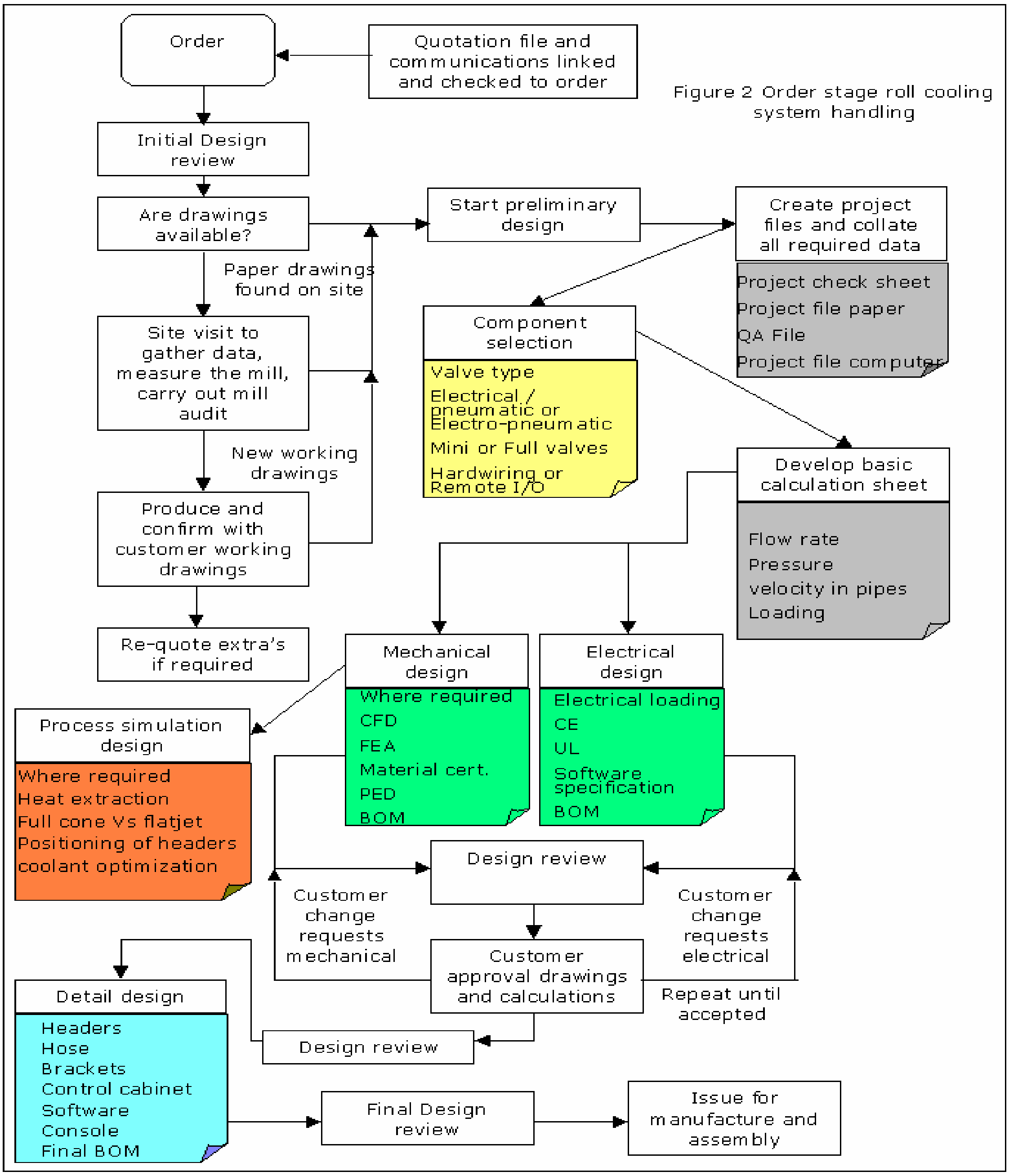


Figure 2 Order stage roll cooling system handling

Figure 2 shows the flow of a project once an order is received

Design Integrity

Stating the obvious, the header design is one of the most important elements of the whole system, in that it will house the spray actuators, which will be in constant vibration and subject to intermittent shock loading. The majority of headers are manufactured out of Stainless steel, although some companies supply in Mild steel and even Aluminium. Where Lechler are involved with creating the spray actuators as part of the roll change rail, it will use a finite element analysis (FEA) model constructed in Solidworks based on CAD drawings developed in AutoCAD. The model is then exported to ANSYS version 8.1 where the analysis is carried out. System variables are defined for steel with a Young's modulus of 210GPa, a density of 7850kg/m^3 and a Poisson's ratio of 0.3. The model was meshed entirely with second order solid elements (type 186) and fully bonded contact elements were used to connect separate components together.

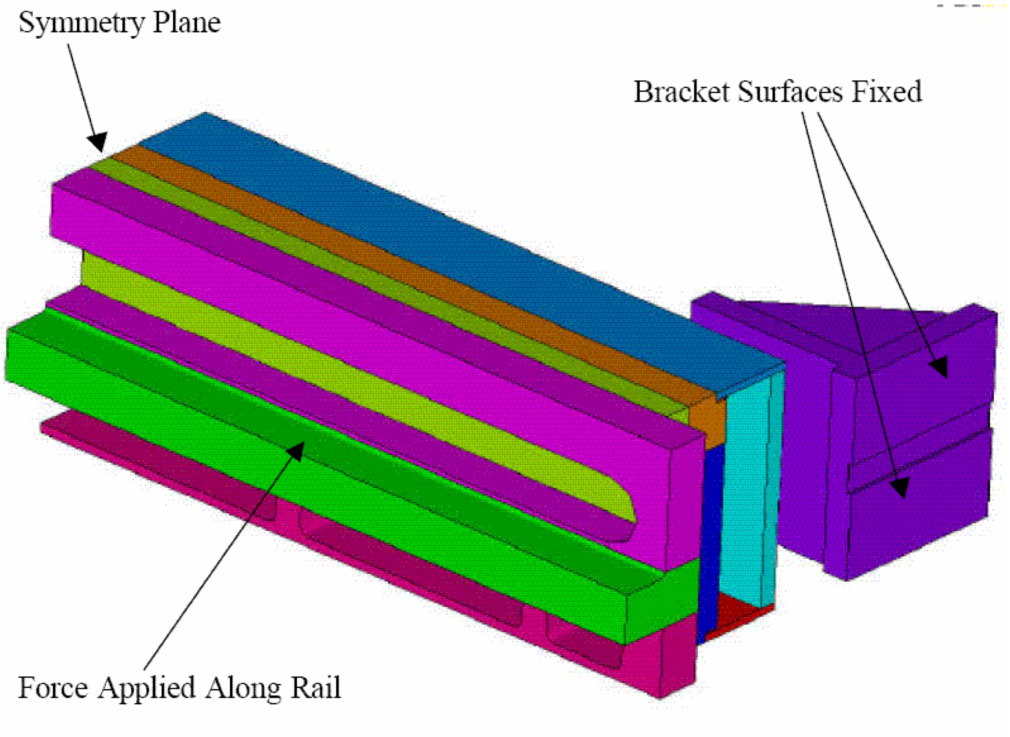


Figure 3 3D graphic of header design

The loading on the header for this application is applied to the top surface of the rail. The total force on the rails is 35kN (as defined by the customer), so as this was a half model, 17.5kN was applied as a distributed load across the top face of the roll change rail of the spray header.

For the top rail, the face of the support bracket - shown in figure 3 - was fully restrained. The results revealed that there was very little stress within both header beams. Figure 4 below, shows the stress intensity in the top header beam. For this model the maximum stress is 94.5MPa, which is concentrated at the bottom corner of the support bracket. Stress within the rest of the beam is lower, generally below 70MPa with the high stresses concentrated around the back plate and top cover plate.

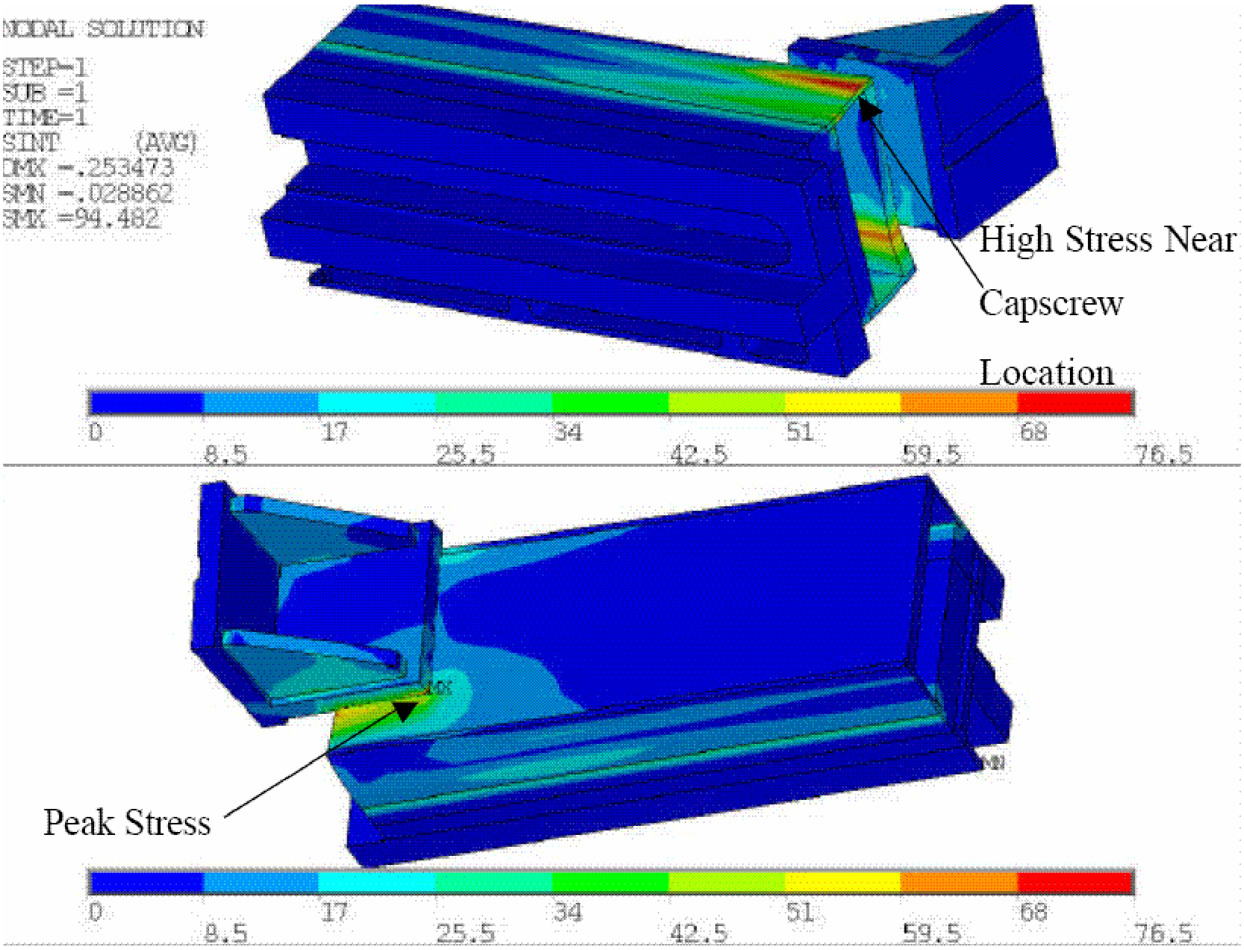


Figure 4 Stress shown within header design

The peak stress occurs at the corner of the support bracket and so it can be treated as a peak stress. Figure 4 also shows that there is much greater stress in the back plate of the spray header than in the bracket itself. This was not unexpected, as the bracket is substantially thicker and stiffer than the back of the spray header. The stresses in the back plate are concentrated around the bracket and do not extend to the areas where holes for the hose connections are located. However, there is significant stress placed on the top cover plate, which is close to where a capscrew is situated.
The engineer will also review and comment upon the vertical displacement of the top spray header roll change rail. In this example the maximum deflection is only 0.24mm for the specified load.

Not every project would demand FEA to be run, but where the spray actuator header is being used in a success critical operation, the roll cooling manufacturer must be able to offer this service. Other advantages from using FEA would be to review the stress of mountings, or fatigue potential in coolant inlets or welded surfaces.

Spray pattern development

As described earlier by my colleagues Forster & Downey(2) Heat transfer to the coolant is dependent upon the dwell time of the coolant on the roll. The time droplets are in usable contact with the roll is brief, due to the tangential forces acting on the droplet from the spray actuator as their sprays impinge upon the roll. What was not considered in that earlier paper was the spray impingement of adjacent spray rows / nozzles from the same or other spray bars.

It is with this in mind that the designer must utilise the maximum distance available to space the rows of nozzles and then ensure that the nozzle is inclined to the optimum allowing the best coverage with a defined band of spray overlap.

Variables the designer must consider:

1. Roll diameter changes, hence spray patterns should be considered for Maximum, Minimum and medium roll size change progression.
2. Spray collisions with mill furniture
3. Spray collisions with other sprays.
4. Spray overlaps are within a 10 to 30%
5. No under spraying allowed.
6. Type of control philosophy – multi-step / single zone coverage or 80/20 selective / basic coverage – uniform or differential cooling duties.
7. Pressure flow variations in spray patterns.

Spray collision with mill furniture or other sprays are a factor of poor design, although the problem maybe associated with the lack of quality information from the mill or out of date mill drawings. This can not be used as an excuse, since the need for mill audits where “unknowns” are present in the quality of mill information is essential. To err is human, but it does not make it anymore expensive at times to solve a problem. The use of more modern CAD packages such as Inventor, used by the authors company, offer greater tools to allow for potential impingement’s to be found at the design stage.

The use of “non-specific” header designs can also lead to such spray collision compromises, since the headers are not positioned into a mill with the same accuracy that is provided with bespoke header design.

The developments of spray patterns that are shown for the three different roll sizes – figure 5. Shows the designer is considering the “sensitivity” of the spray overlap to roll changes. Defining a spray pattern overlap parameter as (pattern width)/pitch *100%, this parameter should not be more than 50% so that the sprays can be effective in giving local changes to cooling during profile control. Ideally, it should be between 10 and 30% through the work roll diameter range. It is also important that the sprays do have some overlap since stripes on the strip can result from gaps between sprays, which are a result of undercooling on the work roll.

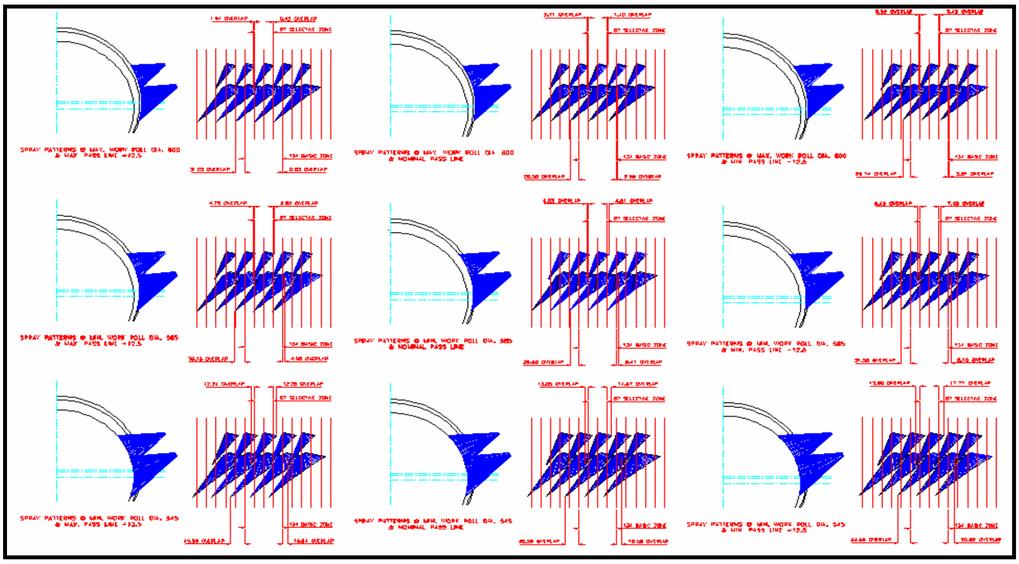


Figure 5 spray patterns with variations in roll diameter

The exceptions to this 10/30% rule is where the designer is working on an 80/20 control philosophy system. These are normally Steel mills or Aluminium hot mills or interstand cooling for steel / Steel hot mill roll cooling, all of which may employ the uses of multiple zone “basic” cooling to create a thermal balance and then have one or multiple rows of nozzles with a single zone coverage to give the “differential” zonal cooling control. The latter is often describe as using the minimal amount of coolant to achieve the work roll operational temperature and then using the maximum amount of coolant to give spot cooling where and when it is required.

The very nature of the roll cooling system to be able to effect the work roll temperature and hence carryout the demands of the flatness control. Excessive overlaps will lead to poor sensitivity between zones and hence the response to the flatness control system will be slow.

Spray positioning

The positioning of the spray nozzles in relation to the work roll and the distance between centres have a major effect upon the performance of the heat extraction that is required.

Table 1 shows the typical spray nozzle spacing are used;

Mill type	Nozzle spacing	Edge controls	Number of rows
Hot Aluminium	75mm or 3”		2 or 3
Cold Aluminium	52mm or 2”	25/26mm or 1 “	2 or 3
Cold Steel	52mm or 2”		1 or 2
Cold copper / brass	52/26mm or 2"/1"		2
Hot Steel mill	75/52 or 3"/2"		2 or 3

Table 1 typical zonal spacings

Many other types of combinations are used, but the majority of systems will comply with the above table. The exact layout of the nozzles will depend upon a number of factors, but usually specified to match the shape control roll or in a hot mill, to the customer preference. It is important to consider the spacing during the design stage when the designer is gathering data. Since at this point if the customer is experiencing process problems the spray actuator can be developed with those process issues in mind. For example a customer could not control the edge temperature of the strip on a Hot mill, this was as a result of poor differentiation of zonal sprays. The spray pattern used was of a flat nature with large overlaps and widely spaced nozzles, which offered excellent uniformity of sprays but switching an individual valve, would do little to affect a localized need for extra cooling. The result was for poor thermal control at the edges of the strip leading to down stream processing problems.

The solution, shown in figure 6, of the above case was to move from 100mm to 75mm spacing and change the angle of the nozzles to a more vertical spray, resulting in excellent zonal sensitivity.

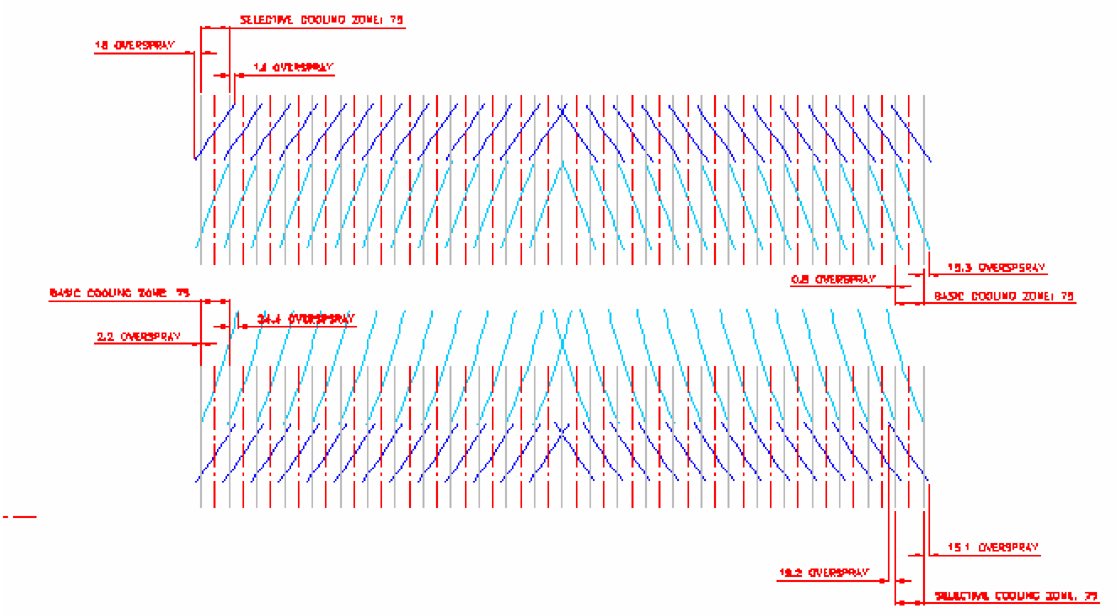


Figure 6 spray pattern design for a Hot aluminium mill

The header location in the mill is defined at the design stage where the designer will determine the optimum workable position for the spray headers. This can be a compromise as mentioned earlier in the paper, but by the ability to manipulate the nozzles spray pattern the designer will be able to minimise the effect of the “compromise”. Customers often consider the design of “special” nozzles will increase the cost of the nozzles or the potential lead-time, as nozzle manufacturers, Lechler are able to produce within the same time period and budget as standard catalogue nozzles.

An example of the location of the spray headers is shown in figure 7. This shows a typical cold steel mill set-up with the 80/20 control philosophy. The basic spray (20%) is used to create a thermal balance and the Selective 80% of coolant available is used zonal to effect local pockets of thermal expansion on the work roll. In this case up to a third of the basic spray is being used to spray into the bite to assist in the roll bite lubrication. Both of the sprays impact tangentially to the roll face, giving the maximum contact with the roll. The Selective spray angle should be designed to be greater that 55^o where possible, to ensure the best coverage to create the maximum heat extraction.

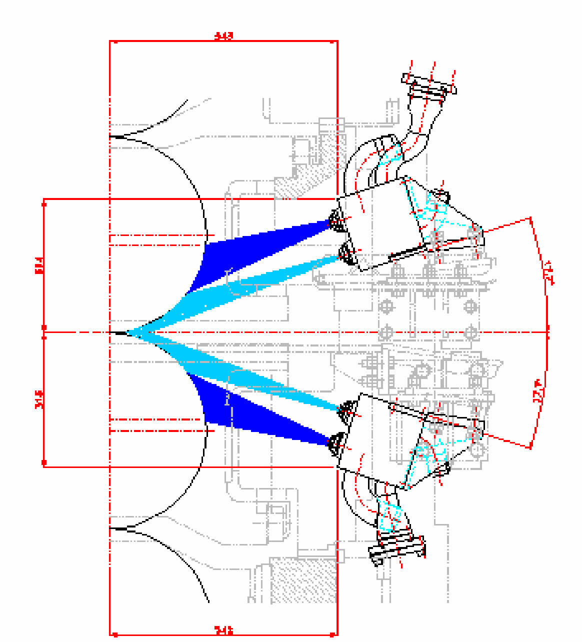


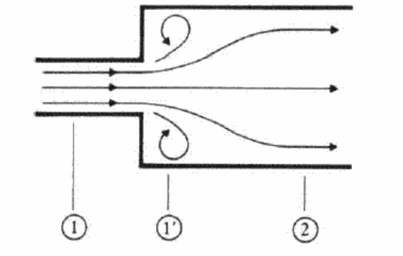
Figure 7 header location in a roll mill

Where the system is based upon single zone coverage all the rows are designed to be contained within the zone that the spray is directed. In this instance the spray philosophy is using all the rows to hit the localised pocket of thermal expansion. By using more rows of nozzles, all the nozzles being directed into the individual matched zone, the heat extraction can be varied with more sensitivity leading to less overshoot of the targeted thermal balanced position.

Pressure drop in headers

Lechler utilise the software fluid modelling package Cfdesign it is an evaluation product using powerful visualization tools, including the Design Review Center and Design Communication Center. CFdesign allows the designer to analyse and optimise the design, placement, and performance of critical components and systems in the design of the roll cooling actuator.

If we now consider some of the common occurring issues when designing the coolant inlets for example l**osses at sudden enlargement.** Consider the flow in the sudden enlargement, shown in figure 8a below, fluid flows from section 1 to section 2. The velocity must reduce and so the pressure increases (this follows from Bernoulli). At position 1' turbulent eddies occur which give rise to the local pressure loss. In a sudden contraction, shown in figure 8b, flow contracts from point 1 to point 1', forming a vena contraction. From experiment it has been shown that this contraction is about 40% (i.e. A1' = 0.6 A2). It is possible to assume that energy losses from 1 to 1' are negligible (no separation occurs in contracting flow) but that major losses occur between 1' and 2 as the flow expands again.



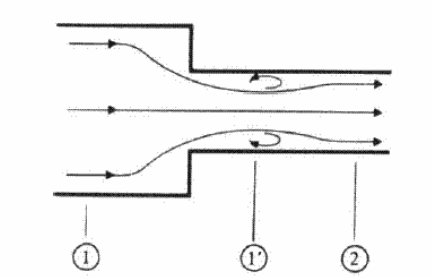
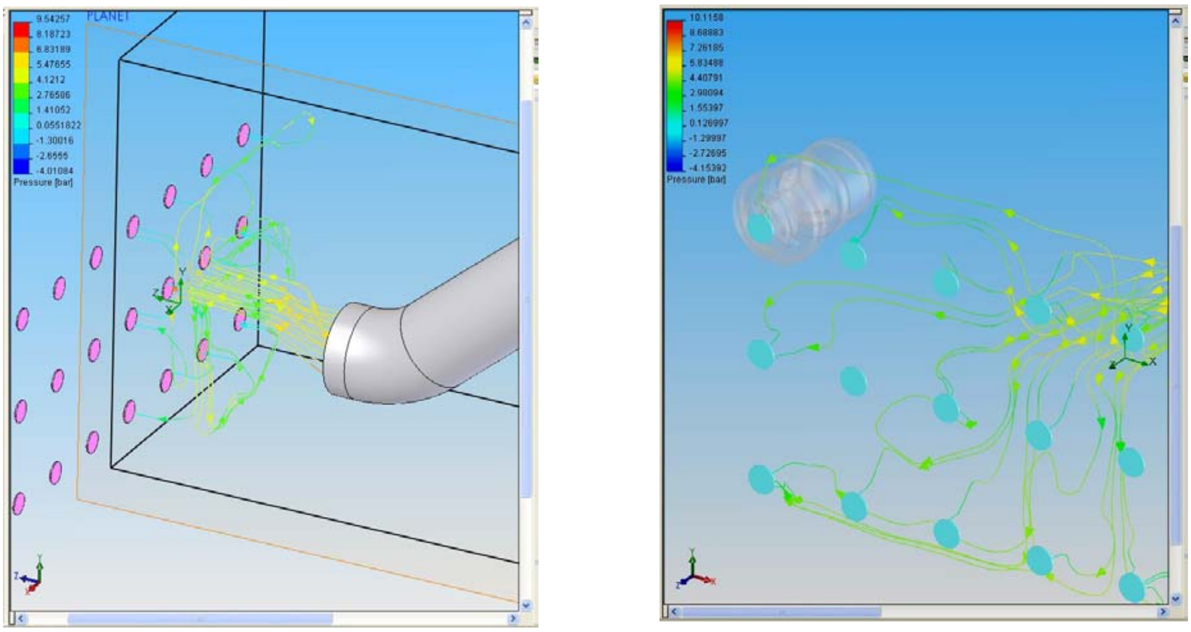


Figure 8a sudden enlargement and 8b sudden contraction

Large losses in energy usually occur only where flow expands. The mechanism at work in these situations is that as velocity decreases (by continuity) so pressure must increase (by Bernoulli).
When the pressure increases in the direction of fluid flows outside the boundary layer has enough momentum to overcome this pressure that is trying to push it backwards. The fluid within the boundary layer has so little momentum that it will very quickly be brought to rest, and possibly reversed in direction. If this reversal occurs it lifts the boundary layer away from the surface. This phenomenon is known as **boundary layer separation.**

The use of Cfdesign allows the designer to consider such conditions that may result in valve / nozzle starvation leading to more turbulent sprays and reduced heat extraction capabilities. Figure 9 & 10 shows a typical plot that tracks the flow into the header and the potential loss in pressure as it flows in the spray valve chamber.

Figure 9 and 10 typical flow plot of pressure in headers



Coolant velocity in pipes and headers

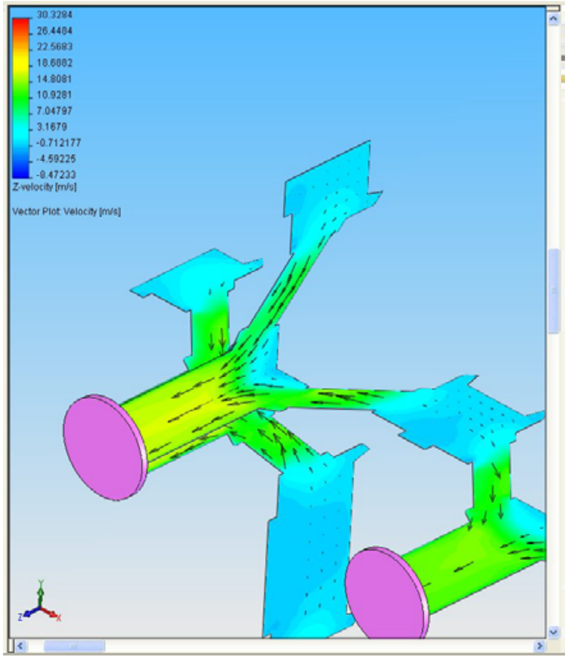
Many different sources will give varying “targeted” acceptable velocity in pipe values. Crane’s indicates 1.2 to 3m/s based upon water. Lechler use 2m/s as the design optimum, but set limit upon which it is not acceptable to work and limits that are within sound engineering boundaries. Typically anything above 5m/s is not recommended and between 3 and 5m/s the customer is asked if extra or larger feeds can be utilized.

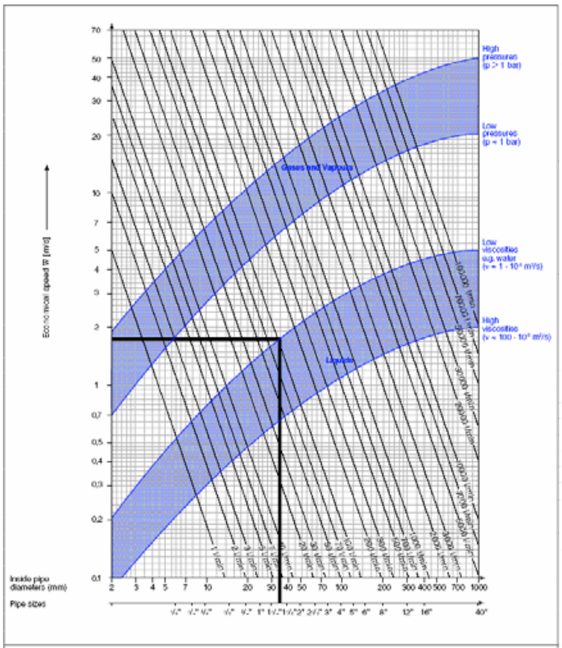
As indicated earlier opening the “inlet pipe-work” up to a larger chamber will reduce the flow velocity and this can come at a cost of turbulence.

Increasingly the use of Cfdesign software will allow the designer the luxury of mapping the velocity in the headers and allow them to consider the effect to a much greater complexity.

Figure 11 indicates a plot showing the velocity of coolant flowing through a Modulax Valve – spray header.

Figure 11 velocity plot from CF design and figure 12 velocity flow diagram





Example: You want to spray a total of 100 l water per minute. Water has a viscosity of $v \approx 1 \cdot 10^{-6}$ m²/s. So in your diagram please look for the intersection of the corresponding viscosity curve and the flow rate line. From the coordinates of this point, you gather the correct pipe inside diameter or pipe size, and the economical flow speed.

Figure 12 is the simple table used to “look-up” and estimates the flow in pipes, this chart is lifted from the Lechler Catalogue, but appears in many other publications. Software is readily available to assist in the determination of flow velocities, always remember that these are estimates and may not be exact to the type of tube that is being used in your manufacture.

Turbulence in headers

It can be observed that a fluid will change from laminar to turbulent as the flow rate is increased. In turbulent flow, water swirls erratically. The velocity at a given point can change in magnitude and direction. The onset of turbulent flow depends on the fluids speed, its viscosity, its density, and the size of the obstacle it encounters. This is of engineering interest since most pipe flows are turbulent in practice even at low flow rates. It is natural to assume that some disturbances are therefore responsible for triggering turbulence and these become more important as the non-dimensionalized flow rate, the Reynolds number, Re, increases (3). (Here Re= Ud/ν, where U is the mean speed of the flow, d is the diameter of the pipe, and ν is the kinematic viscosity of the fluid.) This is explained in much greater detail in the paper **Scaling of the Turbulence Transition Threshold in a Pipe**[(4)]**, by** B. Hof, et al.

If we consider the more practical problems associated with turbulence. Water velocity problems are usually associated with a “closed” loop piping system. Where the need to pump or circulate the water is required, while a roll cooling spray system can be considered an open system it shares a period of time as a closed system. Erosion corrosion occurs at locations where water turbulence develops. Turbulence can be caused by excessive velocity, sudden changes in direction (sharp turns, elbows) and through “flow” obstacles such as burrs and weld excess.

The major contributing factors to this type of erosion corrosion include:

- water velocities exceed 5m/sec
- installation of undersized distribution lines
- multiple or abrupt changes in the direction of the pipe
- burrs on the inside of the pipe
- improper welded joints
- improper balanced system

As indicated earlier Erosion corrosion is the corrosion created by turbulence on a metal surface. It is characterised by surface features with a directional pattern, which is a direct result of the flowing media. Erosion corrosion is most prevalent in soft alloys (i.e. copper, aluminium and lead alloys). Alloys, which form a surface film in a corrosive environment commonly, show a limiting velocity above which corrosion rapidly accelerates. Other factors such as turbulence, cavitation, impingement or galvanic effects can add to the severity of attack.

This can be negated by
- selection of alloys with greater corrosion resistance and/or higher strength. Stainless steel rather than Aluminium
- re-design of the system to reduce the flow velocity, turbulence, cavitation or impingement in the headers.
- Ensure welding is full penetration, pickled or blasted and inspected for smooth transitions

The CFdesign package allows the designer to view the “turbulence” effect within the same model that visualises pressure loss and flow velocity. In figure 13, the header is modeled with the brighter the colour towards the red, being areas of high turbulence.

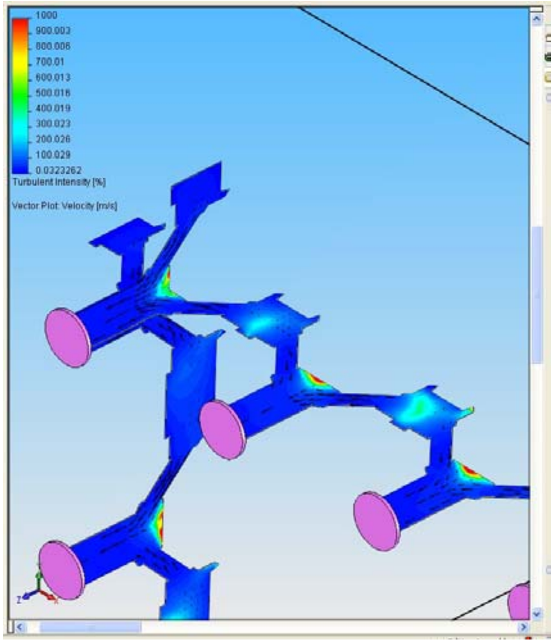


Figure 13 turbulence plot from CFdesign

The final element of this paper will review the use of process simulation, I am grateful for the help of Kyle Smith (some of who’s comments and experience I have included within this paper) at Innoval and the information we receive from the Innoval Spray Impingement Model (ISIM).

The simulation work we carry out with our customers is usually based upon a number of potential outcomes.

1. Assessment of a specified spray cooling system in a comparative basis of the roll cooling system before and after revamp.
2. Assessment of a specified spray arrangement to control roll temperatures for a given set of rolling schedules
3. Assessment of specified spray system and redesign to overcome identified deficiencies and control roll temperatures for given rolling schedules.
4. Assessment of specified spray system and redesign to overcome identified deficiencies

Lechler use the simulation to take the “smoke and mirrors” out of the roll cooling system potential to improve the heat extraction. It can be used to assist in the development of the optimum positioning of headers, nozzle twists.

The information that the designer can then use to adjust the system comes in the form of:

1. Overlap patterns
2. Cooling and Interaction effect from the existing system
3. Cooling and Interaction effect from the proposed system.
4. Optimised header and nozzle location

This information will not give the designer a view of whether the rolls will be cooled to an acceptable level. But it will give a comparative value of before and after the revamp of the cooling system. Many times this is all that is required, but where a process “issue” exist the simulation can be extended to look at the other system variables that are used to consider if the rolls will be cooled to an acceptable level.

In the example that follows, the existing spray patterns where developed into CAD drawings and then presented to the simulation. The immediate result was that the overlaps were outside of the 10 to 30% range normally set for overlaps on roll cooling systems.

Figure 14 shows the spray original spray patterns.

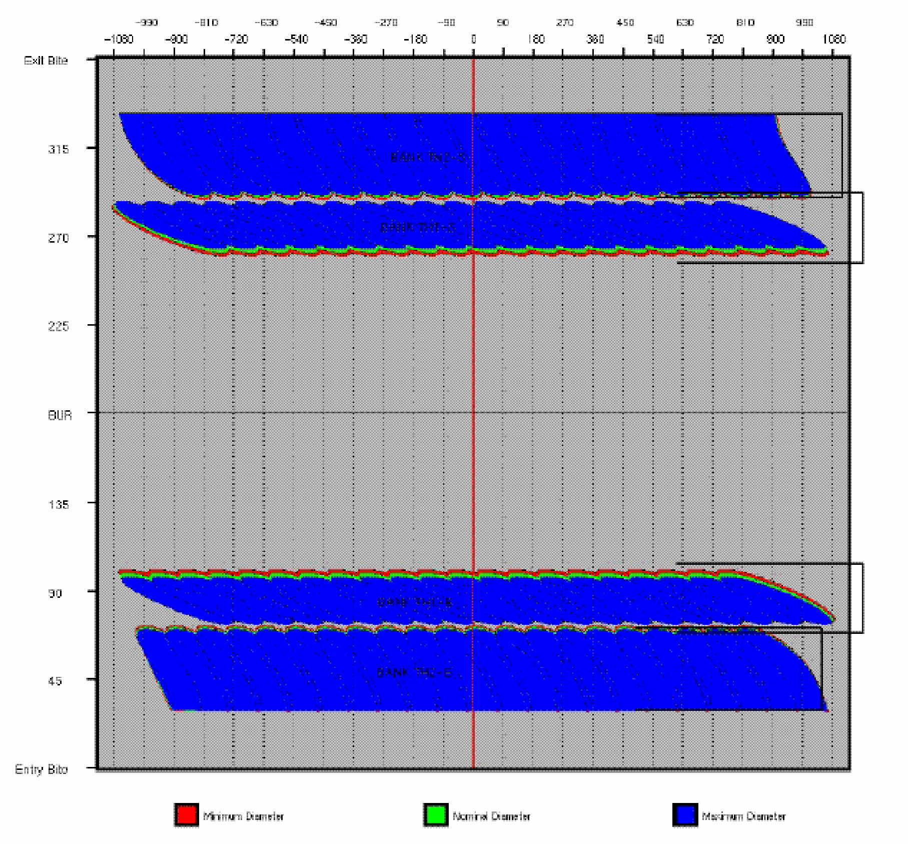


Figure 14 original spray patterns

In this instance the spray pattern over lap ranged from 288 to 393% see table 2, while typical on an interstand roll cooling spray pattern, not helpful when the operator wants to have a differential cooling in a zonal system. From this data the simulation will give the designer a “cooling effect” value.

This becomes the designers benchmark, and from it a number of decisions are made and discussed with the end customer and process operator.

Table 2 overlap and cooling effect data for original systems

Sprays - Existing	Work roll diameter / overlap %				Cooling effect	Interaction effect
	%	%	%		kWm-1C-1	kWm-1C-1
Top Header 1 entry	372	383	393		8.43	
Top header 2 entry	288	290	292		4.98	
Top header 2 exit	288	290	292		4.98	
Top header 1 exit	372	383	393		8.43	
Bottom header 1 entry	356	368	381		8.37	
Bottom header 2 entry	274	274	280		6.36	
Bottom header 2 exit	274	274	280		6.36	
Bottom header 1 exit	356	368	381		8.37	

Parke & Baker(5) produced excellent background reading into the use of simulation when applying coolant to work rolls, providing a detailed explanation into the understanding that relates to figure 15.

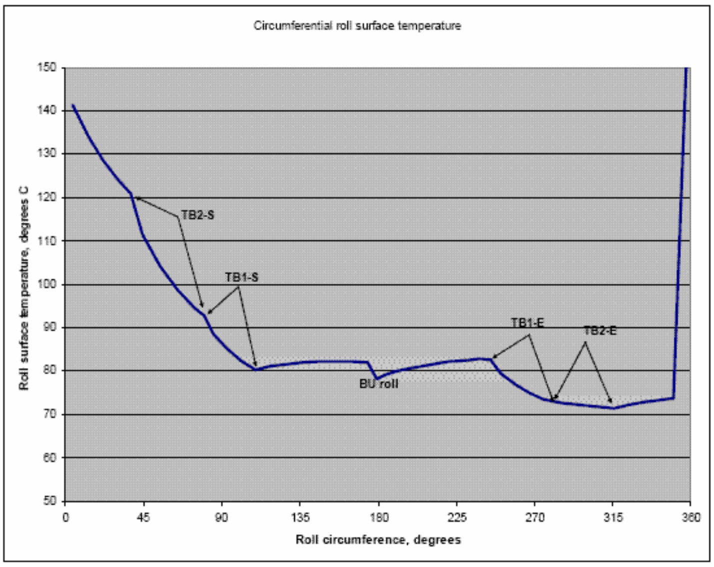


Figure 15 temperature changes with work roll circumference

The simulation provides a diagram of the temperature profile in relation to the work roll circumference as it moves the 360° from roll bite exit to roll bite entry. It shows the effect of the sprays and contact with the back-up roll on the temperature of the roll surface. This again allows the designer to have a reference point.

The designer will consider if the needs of the revamp are to reduce coolant applied or for the mill to run faster or to overcome a particular material rolling bottlenecks. This may lead the designer to provide two sets of nozzles, a provisional set that reduces flow and works the mill at similar heat extraction levels. The second set would offer the mill the full coolant available and the increased heat extraction. This would allow the mill to start-up in a more known operational position. Once the mill operational staff is happy with the cooling system “feel” they can start the change over to allow the bottleneck or faster operational speeds to be implemented.

The designer will present a solution to the customer in the form of figure 16, which indicates the new spray pattern and indicates the heat extraction values that will be achieved. When a simulation is used in this manner, to some degree the “absolute” accuracy of the numbers is irrelevant since the comparison is being made under the same operational conditions and hence the changes in magnitude can be considered as accurate. This is not to say that the calculated values are not correct, but validation on the mill is almost impossible, but the comparative changes can usually be observed by the normal operational instrumentation.

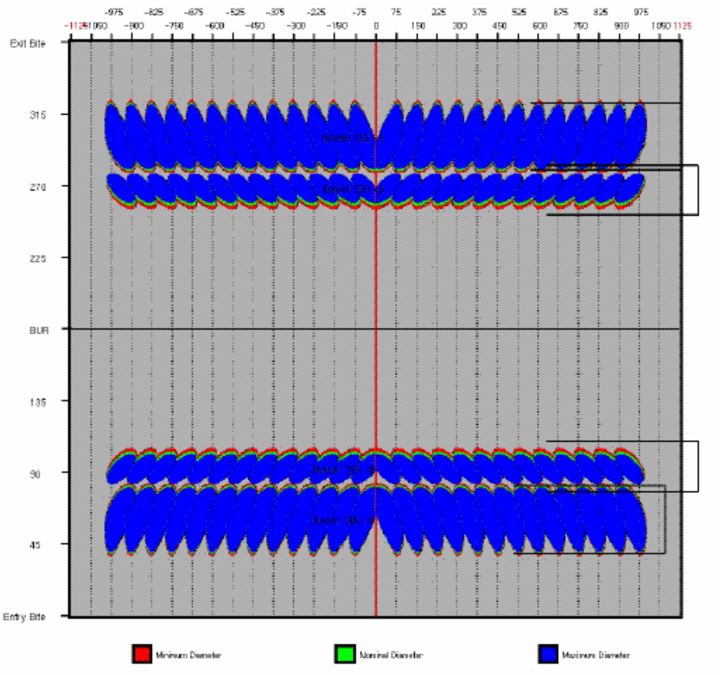


Figure 16 new spray pattern design

Once the spray pattern is determined, overlaps are established and the heat extraction values produced the designer is able to set the flow rates for the nozzles, in this example two sets of nozzles will be provided. Table 3 shows the new data for the "new" work roll cooling system.

Table 3 overlap and new cooling effects against reduced flow and existing flow conditions

Sprays	Work roll diameter / overlap %				Cooling effect	Interaction effect	Cooling effect	Interaction effect
					Reduced coolant	Reduced coolant	Matched coolant	Matched coolant
	%	%	%		kWm-1C-1	kWm-1C-1	kWm-1C-1	kWm-1C-1
Top Header 1 entry	20	24	28		7.6		11.2	
Top header 2 entry	17	19	21		7.1		10.52	
Top header 2 exit	17	19	21		7.1		10.52	
Top header 1 exit	20	24	28		7.6		11.2	
Bottom header 1 entry	25	29	33		7.57	-0.21	11.2	-0.67
Bottom header 2 entry	27	29	32		7.14		10.52	
Bottom header 2 exit	27	29	32		7.14	-0.21	10.52	-0.67
Bottom header 1 exit	25	29	33		7.57		11.2	

To conclude, the critical elements of the work roll cooling system are:

- Work in partnership with your customer
- Develop the solution, once the facts are known about the process requirements.
- Consider the header design, in relation to pressure drop, turbulence and velocity of flow.
- Use defined rules of design and adhere to procedures.
- Utilise the tools of the business to give the customer the assurance that all critical success factors are considered and that they can be demonstrated.
- Where the end customer needs or requires it’s use simulation as a tool for process improvement and design validation.
- Insist that header designs are optimised to the mill environment.
- Insist that nozzles be provided to the optimised spray positioning, allowing compromise leads to losses in efficiency.

BIBLIOGRAPHY

1. N Ishikawa, Y Minagawa, T Doi, H Nagakura, Improving the efficiency of work roll cooling system in Hot rolling process – Furukawa Aluminium Co., Ltd
2. B Forster and G Downey Recent Developments in Roll cooling concepts, (page 1993- 2026)
3. Lord Kelvin, Philos. Mag. 5, 459 (1887).
4. CIVE2400 Fluid Mechanics Scaling of the Turbulence Transition Threshold in a Pipe
5. DM Parke & JLL Baker, Temperature effects of cooling work rolls, AISE publication