A QUANTITATIVE STUDY INTO THE COMPARATIVE EFFICIENCY OF FLATJET AND FULL CONE SPRAY NOZZLES WHEN APPLIED TO THE APPLICATION OF WORK ROLL COOLING

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INTRODUCTION

Many myths exist around the use of spray nozzles in the process of helping to control flatness of Steel or Aluminium strip. Whether in the hot or cold rolling process, flatness is one of the primary factors by which the quality of strip is measured and when it goes wrong can be accountable for poor productivity and lead to mill operating speeds being reduced.

Spray bars or headers have long been used as an actuator for the control of strip flatness. This paper will consider one aspect of this actuation, the comparative effectiveness of full cone sprays against that of flat jets nozzles. It will consider many aspects of the spray pattern on the rolls and review the heat transfer coefficient of each type.

Numerous studies have been done on heat transfer coefficients and the cooling mechanism of water on a hot surface[1-4]. Some have focused on the effect of various spray parameters on roll cooling efficiency[5-6]. Also, many studies have shown that shape control can be achieved with differential roll cooling. [7-10,12] One report[13] was written summarizing much of this research, as well as proposed design concepts for achieving optimal coolant application. These concepts for accomplishing effective roll cooling have been used successfully in both hot and cold mills worldwide. The purpose of this paper is to consider one aspect of the roll cooling process, namely, which spray type, is more effective and to consider the advantages of each type. The results gathered from practical simulation work will be presented and these are discussed along with the possibility for the improvements in spray bar design.

The study was to cover the full spectrum of mill arrangements and material types, but due to time limitations and practically of testing the project was divided into three. This paper will cover the preliminary findings based upon Hot rolling.

BACKGROUND:

As indicated, earlier coolant is an excellent medium to control the product shape and flatness, the Aluminium industry has lead the way in the development of these techniques. This is accomplished by the control of the thermal growth of the work and back-up rolls. Typical location and mounting of headers can be seen in Fig. 2, the condition of the headers, the alignment of the nozzles, and the types of nozzles used, as well as other variables, resulted in sporadic and inconsistent cooling of the rolls. As mills have increased speed, broadened product diversity, and adapted to more stringent quality standards, gaining control of all elements of the rolling process has been a critical objective. Coolant application is one of the key elements. We shall go no further into the actuation in this paper but concentrate on the spray nozzle. Even in such a technically developed operational sectors, some issues appear to be down to opinion. Optimising coolant application requires an understanding of both efficient and balanced application of coolant. Efficient application is readily understood from existing studies. Coolant should be applied to achieve the most efficient heat transfer between the rolls and the coolant.

SPRAY CONTROLS AND HEAT BUILD UP IN THE ROLLS

The main function of a "roll cooling" system is to maintain an even temperature distribution over the work roll, back up or intermediary roll barrel length. Dependant upon mill type it also is used to provide rolling process lubrication, to optimize the rolling loads. But this paper will consider the primary effect of ensuring accurate flatness of the rolled strip, to ensure this the "zonal" roll cooling system must also be able to correct defects caused by heat buildup in the rolls due to the rolling process.

Heat is generated primarily at the interface between the product and work rolls (roll gap), heat is manifested during the deformation of the material and the friction between the product and the rolls as the material accelerates through the roll gap and becomes thinner. This is illustrated in Fig. 3. The heat is then transferred to the work rolls by conduction. In a hot mill, with product temperatures between 820°C/1500°F and 1100°C/2000°F, heat is also transferred to the work rolls in the area adjacent to the roll gap by radiation. Since product temperature is assumed to be uniform, and the deformation and frictional forces are the same for both top and bottom rolls, the heat energy transferred to both is nearly equal at any given time and location across the face of the roll. This assumes, of course, that the rolls have equal diameters and are identical in material content. However, the amount of heat generated can vary significantly across the face of the rolls. Variations in product thickness and profile, chemical and physical properties, impurities, and minor defects result in variations in heat build-up in the rolls, which can cause the rolls to expand unevenly. This expansion can damage the roll surface and, in turn, lead to both shape and surface defects.

As heat is carried away from the roll gap, it diffuses into the roll. The rate of diffusion is dependent on the temperature differential between the surface and the roll core, and the internal thermal conductance of the roll[5].

TYPES OF ROLLING MILLS AND MATERIALS

Most projects commence with grand ideas of making a practical test that covers all applications, in reality the operating conditions of a cold mill and hot mill are as different as chalk and cheese. Hence it was determined that the first part of our study would concentrate on Hot rolling and our tests were built around actual experiences Lechler had gain in recent mill operational set-up.

Coolant spray nozzles can be classified by pattern type. Hollow cone, full cone, flat spray and solid stream, with a number of derivatives of these 4 types. We will not consider the Hollow cone or solid spray patterns as these are not generally used in the roll cooling application.

Axial-flow full cone nozzles achieve a uniform liquid distribution over a circular area. A rotary motion of the liquid is achieved with the aid of swirl or vane inserts inside the free cross section of the nozzle. Liquid is swirled within the nozzle and mixed with non-spinning liquid that bypasses the swirl element, or vane, in some cases, the vane design provides for counter swirl. Liquid then exits through an orifice, forming a conical pattern. Spray formation, liquid distribution, and shaping of droplets are influenced by the dimensioning and functional coordination of the rotary motions and the swirl chamber. Turbulent flows with different axial and tangential speed components lead to overall coarser droplets than with a comparable hollow-cone nozzle. The vane or swirl disc typically limits the free passage through this type of nozzle. Also, the conical pattern from this type of nozzle can be made to resemble a square or oval shape by changing exit orifice design.

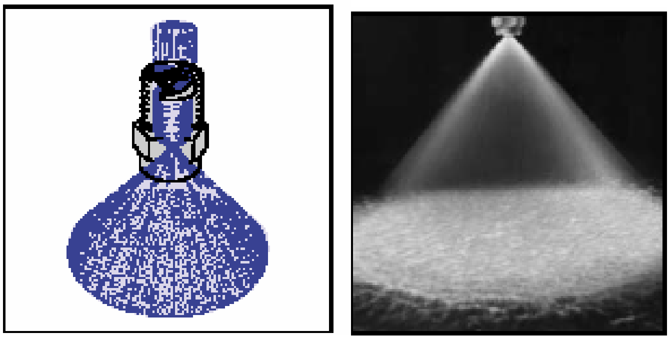


Figure 1 and 2 show the axial flow Full cone nozzle

The spray pattern of flat fan nozzles features a sharply delimited line due to internal flow characteristics. The spray patterns are produced by spraying a solid stream onto an integral profiled deflector surface or by intersecting an angled or profiled external groove with contoured internal cylindrical radius geometry. Modifying the geometric configuration of the nozzle orifices, where the liquid is shaped into flat, fan-like spray patterns, can vary the coverage width. The flat liquid body takes on a laminar form and disintegrates into droplets as its distance from the nozzle orifice increases. Parabolic, trapezoidal or rectangular impact areas are achieved by adequately determining the functional and geometric dimensions.

The deflected flat spray design has a relatively large free passage and thin spray that has a fair amount of momentum.

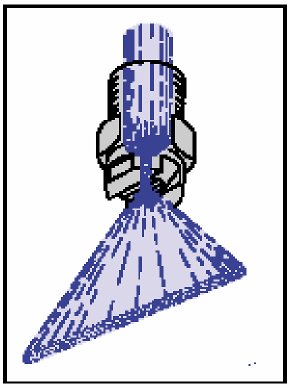


Figure 3 and 4 show the Flat fan nozzle

PRACTICAL TESTS

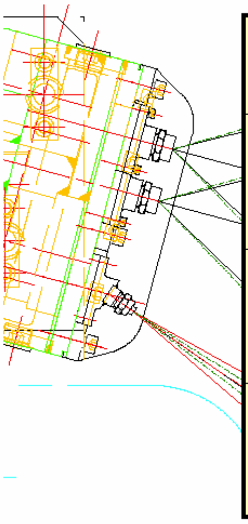
Photo 1 shows the actual Full cone nozzles as compared with flat jet nozzles. A major part of the project was based at Brno University and we were pleased to continue our relation using their laboratory to simulate full-scale rolling mill tests. It was our objective to make direct comparison of the above mention nozzles and further consider the influence of rotational speed, coolant pressure, number of spray bars and distance from roll surface.

Photo 1 Lechler nozzles used in program, from left 652.844, 652.804 and 460.844

THE EXPERIMENT

We set the nozzles and positional parameters of the spray bar in relation to a typical plant condition. The side view of roll and nozzle manifold is in Fig. 5. The spray bar appears to have three rows of nozzles but in effect this is an erroneous observation. The spray bar is actual a two row operation, but to enable the full cone not to overlap (see the spray patterns that follow, in figure 5) and hence effect each spray the row is staggered. Nevertheless, for the tests we defined the spray bar to have three rows of nozzles marked by ***a, b*** and ***c*** in the Table 1. The Flat jet row of nozzles labelled ***a*** is defined in this case to be mainly for lubrication and is not considered as part of the roll cooling simulation. The two rows of full cone nozzles are used for controlled cooling.

Table 1 List of nozzle parameters used in the program



	Existing Nozzles	Test 1 (as existing)	Test 2 (new)	Test 3 (new)
c	460.844.16.CG 18.03 l/min @ 5 bar spray angle 60° R 1/2	460.844.30.CG 15pcs 18.03 l/min @ 5 bar spray angle 60° R ½	652.844 30pcs 19.76 l/min @ 5 bar spray angle 60° FU1	652.804.30 30pcs 15.81 l/min @ 5 bar spray angle 60° FU1
b	460.844.16.CG 18.03 l/min @ 5 bar spray angle 60° R 1/2	460.844.30.CG 18.03 l/min @ 5 bar spray angle 60° R 1/2	652.844 19.76 l/min @ 5 bar spray angle 60° FU1	652.804.30 15.81 l/min @ 5 bar spray angle 60° FU1
a	697.809.16.40.15.0 15.81 l/min @ 5 bar spray angle 40° dove tail FU3 fix	652.803 15.81 l/min @ 5 bar spray angle 45° FU1	652.803 15pcs 15.81 l/min @ 5 bar spray angle 45° FU1	652.803 15.81 l/min @ 5 bar spray angle 45° FU1

The test header uses two rows of cooling nozzles as shown in Table 1. The experimental tests compare cooling with the use of one, two and three rows of nozzles. Circumferential velocity of 1.0 m/s was used as the basis for the tests, but tests were also carried out at 2.5 m/s. Stand off distance was set to 100 mm from the nozzle tip to the roll surface. Four tests, (experiments 13-15) are for the conditions, where distance is increased from “standard” 100 mm to 150 mm. This was done to determine the effect on overlapping of the sprays and to see the effect on the cooling conditions.

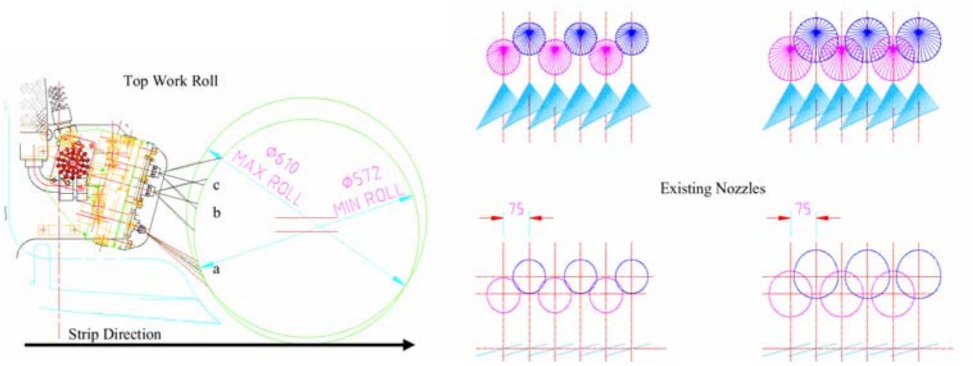


Figure 5 Spray bar and spray patterns

Table 2 schedules the tests that were carried out. The rows ***b*** and ***c*** with full cone cooling nozzles (test 1) will be compared to the flat jet nozzles (test 2 and test 3). For the purpose of the test the two closest flat jet nozzles were taken, since an exact like for like flow rate was not available. The nozzle 652.844 has a higher flow and nozzle 652.804 a lower flow. Since it was considered that the flow or volume of water on the roll was the effective medium for roll cooling, the pressures used was adjusted to develop equal amounts of flow for the flat jets and full cones. The figures in are shown in brackets within Table. 2. The test was carried out at three-pressure ratings 3, 5 and 7 bar.

Table 2 List of the experimental conditions

Experiment	Nozzle	Pressure Bar	Velocity M/s	Distance mm	Used rows	Remark
1	Cone, 460.84	3	1	100	2	Basic full cone
2		5				
3		7				
4		5			1	
5		5			3	
6		5	2.5	100	2	High speed
7	Flat, 652.84	3 (2.5)	1	100	2	Basic flat
8		5 (4.2)				
9		7 (5.83)				
10		5 (4.2)			1	
11		5 (4.2)			3	
12		5 (4.2)	2.5	100	2	High speed
13		5 (4.2)	1	150	1	Distance
14		5 (4.2)	1	150	2	Distance
15		5 (4.2)	1	150	3	Distance
16		5 (4.2)	2.5	150	2	Dist + Speed
17	Flat, 652.8	3 (3.9)	1	100	2	Basic flat
18		5 (6.5)				
19		7 (9.1)				
20		5 (6.5)			1	
21		5 (6.5)			3	
22		5 (6.5)	2.5	100	2	High speed

EXPERIMENTAL PROCEDURE AND DATA PROCESSING

The experimental equipment at Brno has been described many times; here is a brief description of the test methods employed. The experiments use one, two or three rows of nozzles. Seven temperature sensors are embedded in the test roll, sensor No. 4 is located in the centre of the roll width, the others are spaced at 55 mm centres (configuration is shown Fig. 6). Spray covers the entire roll surface and data from all of the sensors are used to develop average values.

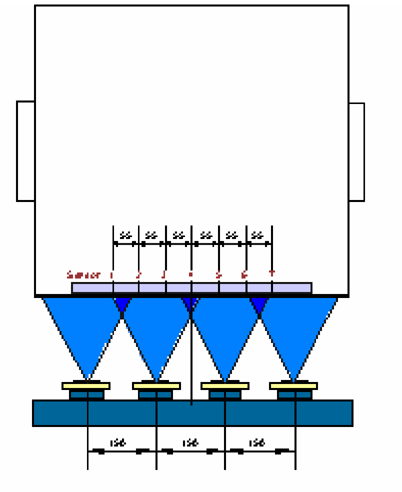


Fig 6. Scheme of positions of sensors and nozzles

Preparation for an experiment starts by putting an electric heater with a test plate on the roll. The roll is stationary during heating. The experiment starts as soon as the temperature of the test plate reaches 340°C. The heater is removed, rotation starts and the pump is switched on with the closed water deflector plate. The deflector is synchronised with the position of the test plate, to ensure that water is not sprayed on to the test plate. The control is via a computer control to ensure the deflector plates opening and closing at exactly the same instants for all experiments.

EVALUATION OF THE MEASURED DATA

Once the experiments had been run and data gather, the measured temperatures go through a standard inverse procedure[14]. Surface temperature, HTC and heat flux are computed. Each data point carries information about position (angle). The results are plotted and the points of the beginning and the end of each spraying time zone are found. The data of the "time" order are converted to the position order**.** The point of 0 mm is selected; see the scheme in Fig. 7. Real nozzle arrangement is in Photo 2.

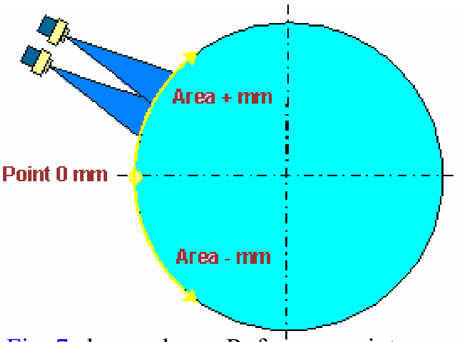
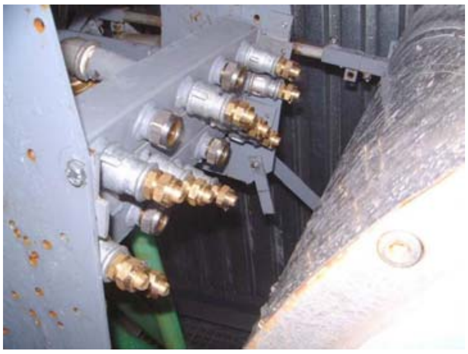


Fig. 7 above, shows Reference point on surface and positive and negative co-ordinate

Photo 2 Below, Nozzle configurations for experiment with three rows of flat jet nozzles.



The position is connected with the roll geometry not with the positioning of the nozzles.
It was decided to use the distances on surface and not angles to simplify the usage of the obtained results for applications with different diameters of the roll. A special program for interpolation of the HTC by a single curve is designed. The program uses convolution with Gaussian distribution and export vector of HTC. This vector is for HTC values from -1000 mm to +1000 mm with 1 mm increment. The vector is the main result of the experiment and is used as the description of the boundary conditions for numerical models of temperature fields in a roll. The data files can be directly used in the Cool Roll computer simulation program. Dr Raudensky and his staff will be pleased to answer any questions relating to the specifics of the number crunching.

RESULTS OF MEASUREMENTS Table 3 List of the experimental results

Experiment	Nozzle	HTC **AVERAGE** **W/m2K**	HTC **RELATIVE**	Pressure bar	Velocity m/s	Distance mm	Used rows	Remark
1	Cone, 460.844	**10.532**	**63%**	3	1	100	2	Basic full cone
2		**13.427**	**80%**	5				
3		**14.694**	**87%**	7				
4		**10.030**	**60%**	5			1	
5		**16.706**	**100%**	5			3	
6		**15.261**	**91%**	5	2.5	100	2	High speed.
7	Flat, 652.844	**8.722**	**52%**	3 (2.5)	1	100	2	Basic flat jet
8		**10.255**	**61%**	5 (4.2)				
9		**11.100**	**66%**	7 (5.83)				
10		**5.991**	**36%**	5 (4.2)			1	
11		**14.040**	**84%**	5 (4.2)			3	
12		**10.782**	**64%**	5 (4.2)	2.5	100	2	High speed.
13		**6.797**	**41%**	5 (4.2)	1	150	1	Distance
14		**10.990**	**65%**	5 (4.2)	1	150	2	Distance
15		**14.542**	**87%**	5 (4.2)	1	150	3	Distance
16		**11.509**	**68%**	5 (4.2)	2.5	150	2	Dist + Speed.
17	Flat, 652.804	**9.008**	**54%**	3 (3.9)	1	100	2	Basic flat jet
18		**10.942**	**65%**	5 (6.5)				
19		**12.027**	**72%**	7 (9.1)				
20		**5.328**	**32%**	5 (6.5)			1	
21		**15.004**	**89%**	5 (6.5)			3	
22		**11.083**	**66%**	5 (6.5)	2.5	100	2	High speed.

The results of experiments follow with average values of HTC in the Table 3 being computed for surface interval from +200 to -700 mm. Relative numbers (in percent) is computed with respect to the maximum obtained HTC value (experiment 5). Information about type and description of experiment can be found in Tables 1 and 2. Position of X=0 mm is on the roll surface on the level of roll axis (see Fig. 7).

RESULTS AND CONCLUSIONS

A number of graphs could be plotted for the experiment

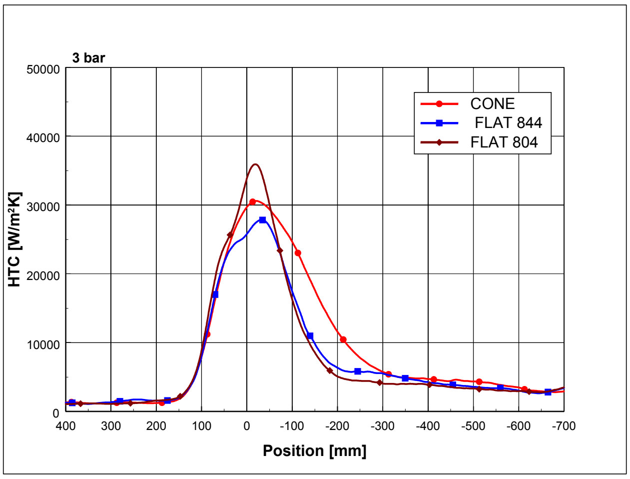


Fig 15. Cooling intensity for pressure 3 bar, 2 rows (experiments 1, 7, 17)

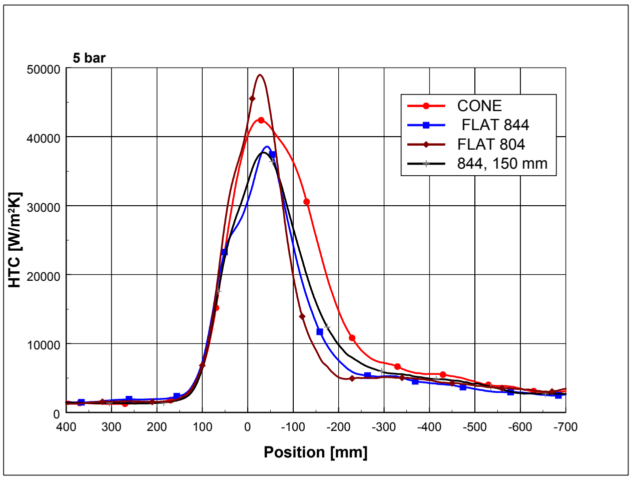


Fig 16. Cooling intensity for pressure 5 bar, 2 rows (experiments 2, 8,14 &18)

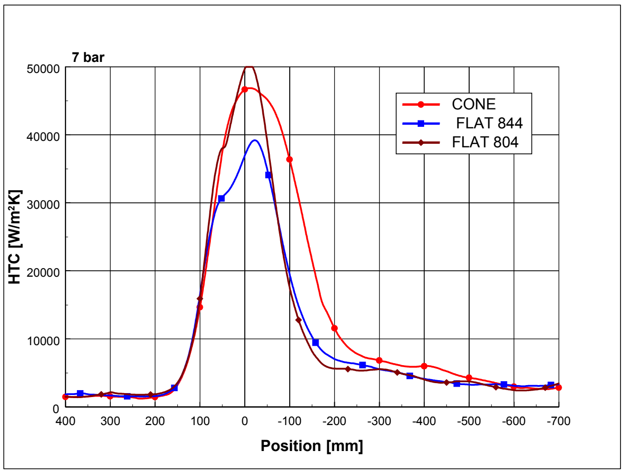


Fig 17. Cooling intensity for pressure 7 bar, 2 rows (experiments 3, 9, 19)

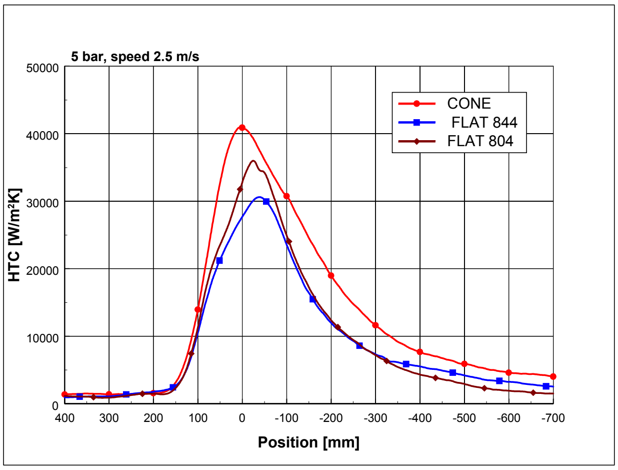


Fig 18. Cooling intensity for pressure 5 bar, 2 rows **Increased Velocity** to 2.5m/s (experiments 6,12,22)

COMPARISON OF NOZZLES

In all the conducted experiments maximum cooling intensity is seen when full cone nozzles are used. Figs. 15-19 shows the distribution of heat transfer coefficient, from these it is observed that Full cone nozzles cover a larger area on the roll surface and hence a better HTC is achieved. Flat jet nozzles reached higher maximum values of HTC but full cone nozzles has wider HTC curve and higher average value of HTC (see Tab. 3). The most visible difference is in Fig. 26, where direct comparison of these three nozzles for pressures of 3, 5 and 7 bar is shown. Table 4 considers the relatively levels of HTC and the highest value for the Full cone nozzles to be a maximum or 100% then we can determine how much less the flat jet nozzles are:

	Pressure 3 bar	Pressure 5 bar	Pressure 7 bar
Full cone 460.844	100%	100%	100%
Flat jet 652.844	82.8%	76.4%	75.5%
Flat jet 652.804	85.5%	81.5%	81.8%

Hence it would appear that with this configuration, flat jet nozzles have about 20% lower cooling intensity in comparison to the full cone nozzles.

Fig 19. Cooling intensity for pressure 5 bar, values for 1,2,3 rows of Full cone nozzles (experiments 4,2,5)

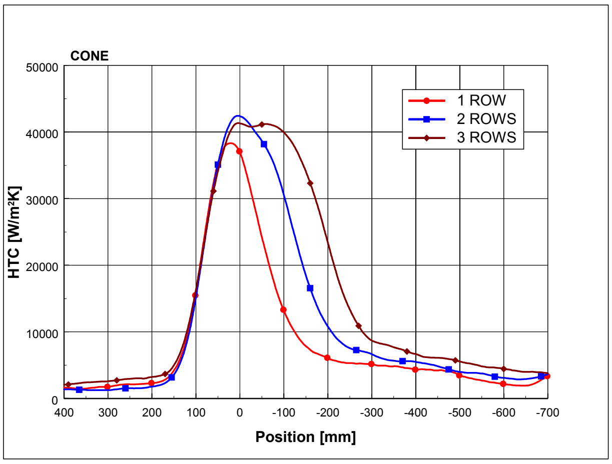
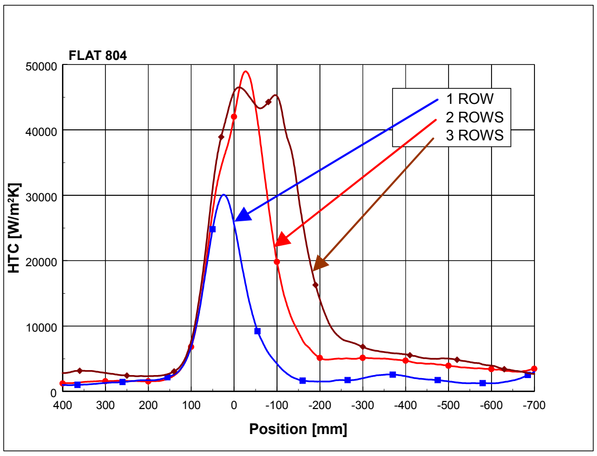


Fig 22. Cooling intensity for pressure 5 bar, values for 1,2,3 rows of 652.804 Flat jet nozzles (experiments 20, 18, 21)



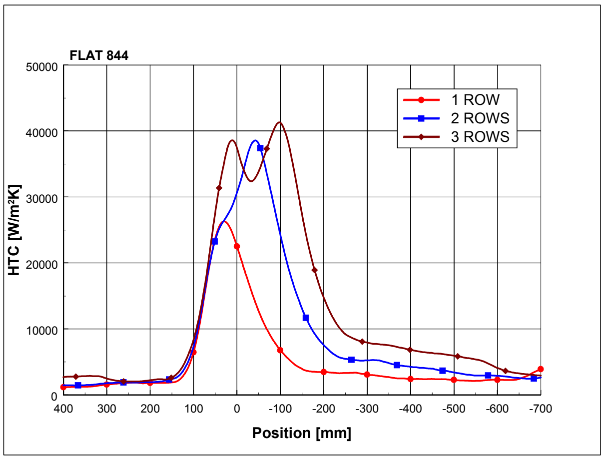


Fig 20. left, cooling intensity for pressure 5 bar, values for 1,2,3 rows of 652.844 Flat jet nozzles (experiments 10, 8, 11)

NUMBER OF SPRAY BARS

All the nozzles were tested with one, two and three rows of nozzles. Figures 19, 20, 21and 22 show the results, for nozzle 460.844, 652.844, 652.844 (but with increased distance) & 652.804 respectively. It can be observed that the performance of the Flat jet nozzles for a single spray bar is not reaching the "maximum" cooling intensity, as seen with that of the one row full cone nozzles. Figure 23 shows average values of HTC and that they are linear with the number of spray rows.

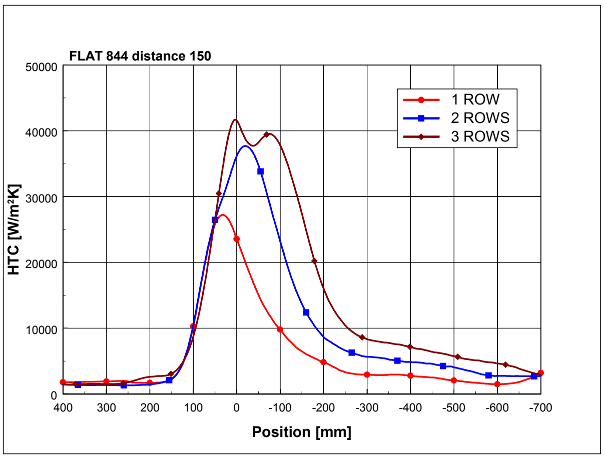


Fig 21. Above, cooling intensity for pressure 5 bar, values for 1,2,3 rows of 652.844 Flat jet nozzles. With increased standoff to 150mm (experiments 10, 8, 11)

DISTANCE EFFECT

The distance effect has been considered a number of times, in our tests it was seen that between the 100 mm and 150 mm, distances, the differences in HTC are not significant. Although HTC values are greater for larger "standoff" distance. Numbers can be found in the table 5 to the below.

Flat jet 652.844	Distance 100 mm	Distance 150 mm
One row of nozzles	100%	113.4%
Two rows of nozzles	100%	107.2%
Three rows of nozzles	100%	103.6%
Two rows, velocity 2.5 m/s	100%	106.7%

Fig 24. Comparison of cooling intensity for distance 100mm (solid line) and 150mm (dash line) for pressure 5 bar, for 1,2,3 rows of 652.844 Flat jet nozzles

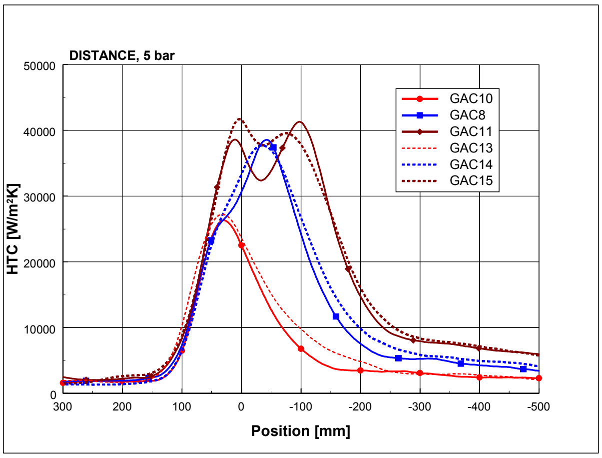


Fig 25. Comparison of cooling intensity for velocity 1.0m/s (solid line) and for 2.5m/s for pressure 5 bar, values for three types of nozzles

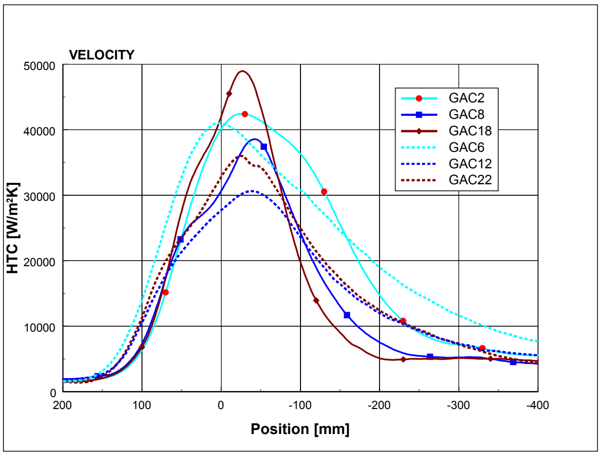


Fig 23. Average value of heat transfer coefficient for pressure 5 bar, for 1, 2, 3 rows of nozzles

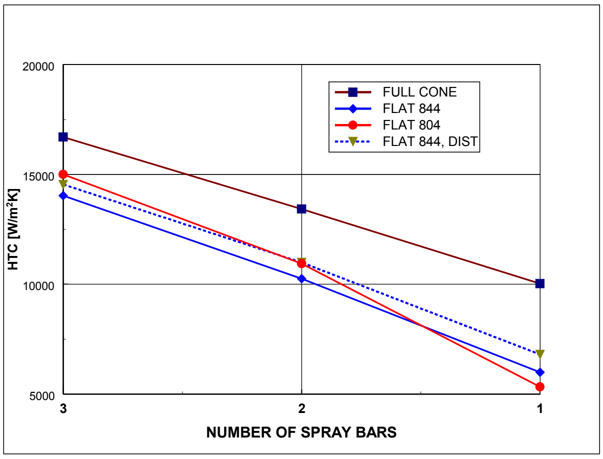
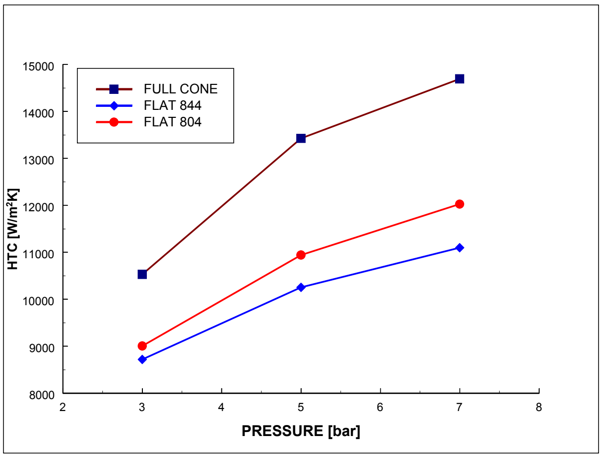


Fig 26. Average values of heat transfer coefficient for three used pressures and three types of nozzles



PRESSURE EFFECT

Predictable results for pressure where observed, in detail Fig. 15, 16 & 17 (for pressure 3, 5 & 7 bar, respectively) should be compared. An interesting observation was the increase of width (spray influenced area) for the lowest pressure of 3 bar and this could be worthy of further future evaluation. Fig. 26 showed the relative values of average HTC and again the flowing table 6 can be used for comparison of the results, with pressure at 5 bar taken to be 100%.

	Pressure 3 bar	Pressure 5 bar	Pressure 7 bar
Full cone 460.844	78.5%	100%	109.5%
Flat jet 652.844	85.0%	100%	108.2%
Flat jet 652.804	82.3%	100%	109.9%

The increases of HTC with pressure are similar for all nozzles. The biggest difference was found for full cone nozzle and pressures 3 and 5 bar.

EFFECT OF PRESSURE FOR EQUAL FLOW

As indicated earlier two sizes of flat jet nozzles were used, 652.844 (19.76 l/min at 5 bar, bore size 5 mm ∅) and 652.804 (15.81 l/min at 5 bar, bore size 4 mm ∅). Pressure was varied to maintain a constant flow, results can be compared in Figs. 15-18, 23 and 26. No major differences of the average values of HTC were observed but the results clearly show that usage of high pressure (for constant flow) provide more intensive cooling. Results indicated that higher pressure gives an increase in HTC peaks of about 20%.

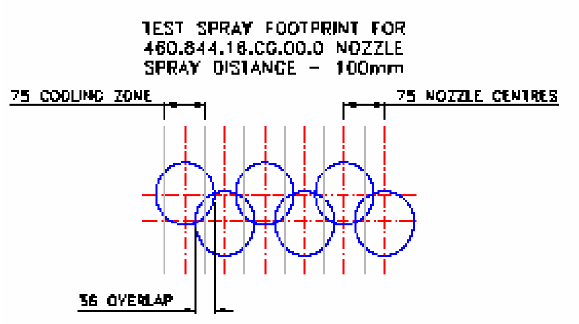
VELOCITY EFFECT

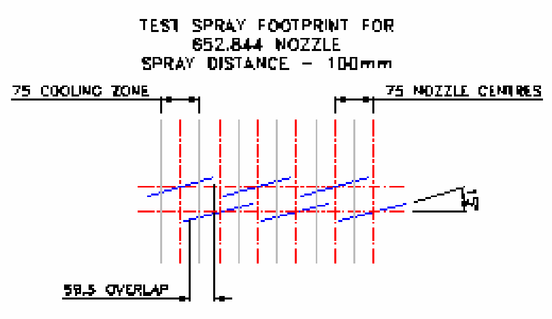
HTC distribution is flatter and wider for higher velocity. Comparison of the average HTC values is in the following table 7 (values for velocity of 1.0 m/s was taken as a reference).

	Velocity 1.0 m/s	Velocity 2.5 m/s
Full cone 460.844	100%	113.7%
Flat jet 652.844	100%	105.2%
Flat jet 652.844 increased distance	100%	104.7%
Flat jet 652.804	100%	101.3%

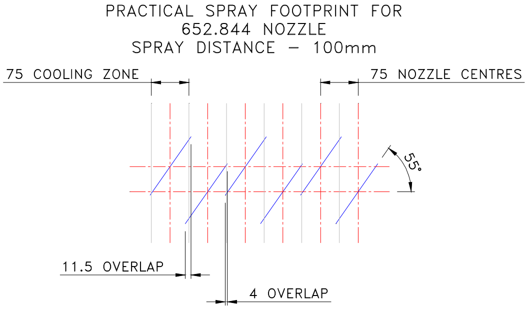
Higher velocity showed a small increase of HTC. This was a surprise and contradictory to previous experience. It is determined that since the direction of spray and direction of rotation is the same, water is driven out from the impact area and impacting jet from the first row of nozzles reaches clear surface not covered by water. Also, and probably more important is the speed effecting the layer of water on roll surface, faster motion leads to a thinner layer and impacting water will be more effective. Consider thought, the opposite will occur for the cooling of the upper roll at the exit side. In this instance the water sprays will be against the movement of roll surface, thus decreasing the intensity of cooling. Secondly, the water flowing on the roll surface will be driven back to the impact area by movement of roll. It will be important to carry out further studies in to roll speed to clarify the observations.

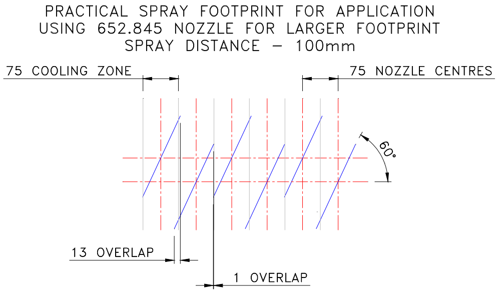
LIMITATION OF THE CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK





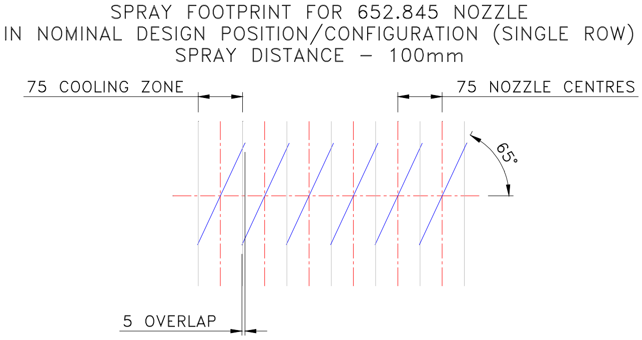
Evidence from the experiments indicates that full cone nozzles are the correct choice for a "Hot mill" cooling system, but consider that the experiments did not use an "optimised" flat jet nozzle, rather an off the shelf nozzle, (Fig 8 & 9). In practise Lechler would not use this for a roll cooling system design.





The above figure 8 & 9 shows the actual effect of the Full cone spray patterns and the mounted positions in the tests. Like wise the following figure 10 & 11 shows the flat Jet spray patterns based upon the tests. The following is a better approximation with the existing test nozzles, this still would not be to an optimised Flat jet design since it is showing overlaps that would not normally be acceptable. Nevertheless using the spray patterns in this orientation would be a greater approximation to how a practical system would be designed. The spray pattern would lead to less overlap and may have an effect on the HTC due to this change.

The Figures 10 & 11 again are a comprised design for flat jets spray positions, a more realistic spray pattern with the spray nozzle footprints covering more of the roll within the zone. Still not ideal in that it maintains the uneven zones of the nozzles arrangement on the test header. This should increase the surface area that the flat jet covers and hence gets closer to approximation the HTC of the full cones. The figure 12 use the same nozzles but with the correct header positioning of the nozzles. This results in a minimal overlap of the sprays and would be to Lechler standard design principles. This has increased the spray pattern coverage by 30% and it is expected that the performance will approximate that of the full cone nozzles. These tests are underway and the results should be available for delivery with the paper.



FUTURE WORK

The above-indicated experiments will be carried out to determine what effect we have with an optimised flat jet spray configuration. We will also model, next a cold rolling mill coolant spray configuration and detail a study in the manner of this paper. We will also try to consider further:

- Velocity of the roll and the cooling effects.

- Effects of cross talk between zones, be that for flat jet or full cone.
- Comparative performance of the 80/20 control philosophy, where a set a “base” roll temperature and lubrication with the 20% and then hit the roll with cooling in zones. The cooling is switched on and off with the zonal requirements to control the temperature / shape and the 3:1 or 7:1, where either 1 of 2 or 1 of 3 sprays are always spraying and hence the amount of coolant if increased to increase the HTC effect.
- HTC values achieved when a valve is pulsed at different rates.

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