A Brief History of Front-End Research and Latest Developments

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1 Introduction

This paper will cover some of the historic highlights of the development of front-ends during the last 200 years. It is also intended to give a phenomenal description of the functioning of a front-end. Illustration and proof of the examples is provided by some of the results of the tests with the RTM 54 steam locomotive.

Notion

The discussion is about the use of exhausted steam to create artificial draught in the boiler of steam locomotives.

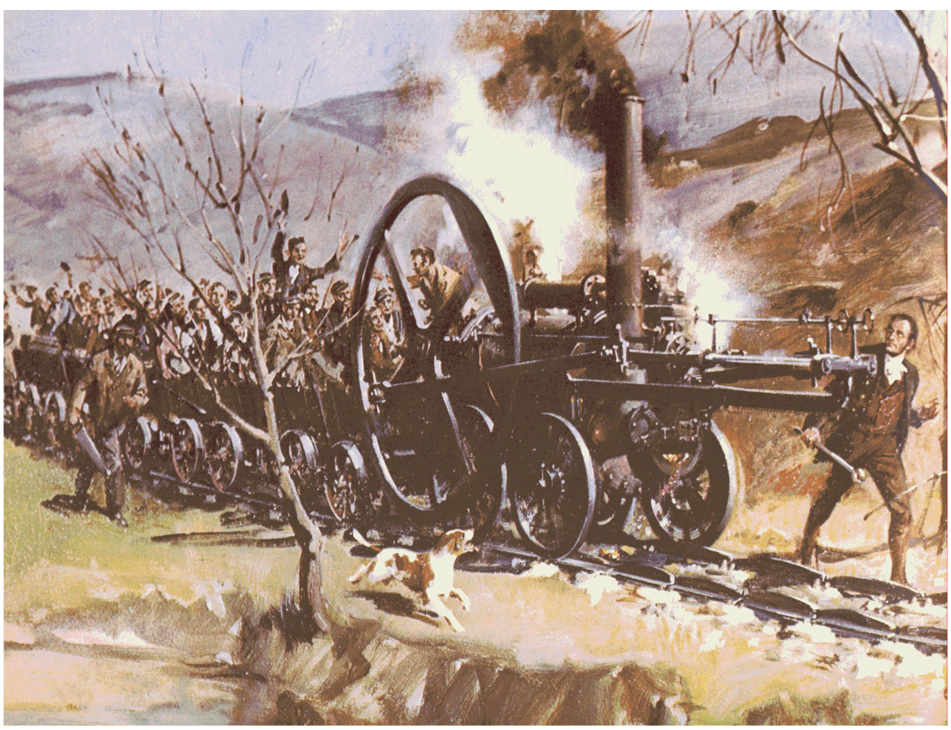


Figure 1 Terence Cuneo's painting of the first steam locomotive

The history of the front-end started with Richard Trevithick, who mounted a blast pipe from the cylinders to the chimney, and turned its orifice upwards. The 20th century painting by Terence Cuneo, present in the Welsh National Museum, shows this detail together with the feedwater heater around the blast pipe. The picture shows the joyous moment it represents, but this author has some reservations about the way Trevithick is represented, walking with a spanner in his hand. Locomotive owners and engineers have a common and lasting tendency to be on the locomotive themselves!

Some 60- years later the first serious research on the subject was started by Prof. Zeuner[1]. He used a simplified model of a front-end. During the tests he found that certain dimensional ratios in the front-end gave an asymptotic limit to its performance. In Figure 2 the ratio of the chimney to the orifice diameter is given by *m* and that of the gas entrance diameter to that of the orifice by *n*. The graph shows that for instance more than 50 units of air, shown on the vertical axis, could not be ejected if the ratio *m,* the different curves, was 16 or less, independent of the value of *n*, shown on the horizontal axis.

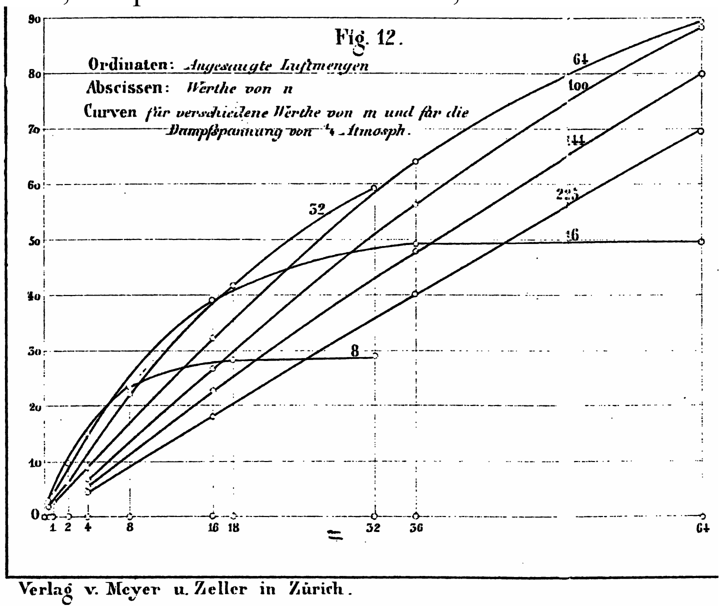


Figure 2 Zeuner, graph showing limiting dimensional ratios[2]

The great step forward of Zeuner was his formulation of the relation between the vacuum in the smokebox the steam and gas masses and their velocities: the Zeuner equation. Figure 3 shows it in its original published form.

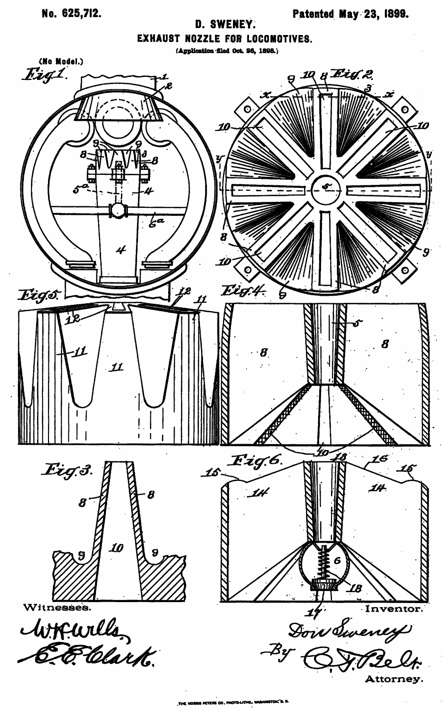
Diese Gleichung ist aber für die gewöhnlichen Fälle einer Vereinfachung fähig. Die angesaugte Flüssigkeit verliert nämlich beim Eintritt in das weite Gehäuse *C* ihre Geschwindigkeit gewöhnlich gänzlich, man kann daher w_0 der Null gleichsetzen; geschieht das in vorstehender Gleichung, so ergiebt sich nach einigen einfachen Reductionen:

$$\frac{p_0 - p_x}{\gamma_1} = 2\left\{\frac{Q}{Q+Q_2} \cdot \frac{w w_1}{2g} - \frac{w_1^2}{2g}\right\} \qquad (60)$$

Auch diese Gleichung bedarf weiterer Umformungen; diese Umänderungen will ich aber unter der ausdrücklichen Voraussetzung vornehmen, dass im Apparate k e i n e plötzlichen Dichtigkeitsänderungen stattfinden. In allen Fällen, wo man bis jetzt Flüs-

Figure 3 Original text of Zeuner with his equation[3]

Next in the line of highlights is Sweney[4], who as a postgraduate student, defined his orifice with 8 rectangular slits. Given its measured performance against conventional circular orifices it was very superior and it is a pity that it remained relatively unknown. It would take another 40 years before Kiesl used the similar version with 6 slits named after him.



Sweney used locomotive 420 of the Illinois Railroad for his tests. Figure 6 is a contemporary photo and was probably made during the test period.

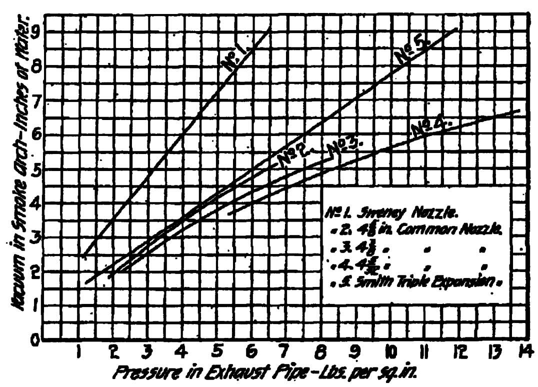


Figure 4 Sweney performance improvement[5]

Figure 5 Sweney patent drawing[6]

Figure 6 Ill.R.R. locomotive 420 probably during Sweney tests

In 1926 the Belgian Legein[7] was one of the early users of a double chimney. However, different from other users he realized what he was doing: increasing the relative length of the available chimney by some 40%.

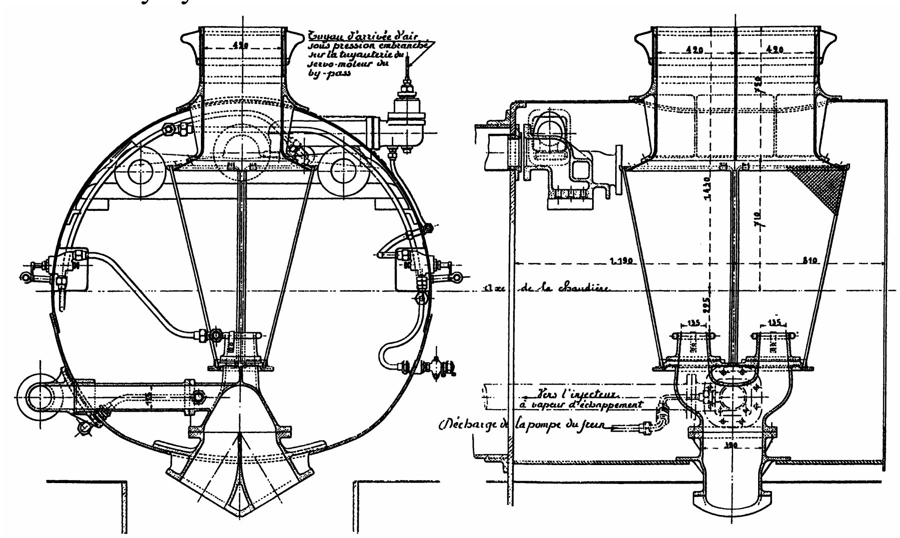


Figure 7 Belgian Railways Pacific type 10 with double chimney[8]

The Frenchman Chapelon[9] published the results of his front-end system, the Kylchap, in 1928. The orifice ejects steam into a 4-lobe splitter. This device was patented by the Finnish driver Kylälä[10]. The Kylälä cowel ejects into a conventional circular cowel which ejects on its turn into the chimney. The picture shows the double Kylchap, not unlike the one used in the LNER A4 Pacific steam locomotive "Mallard", present in the main exhibition hall of the NRM. The double Kylchap allowed a change from one orifice of 5.5 inches to two orifices of each 5.5 inches diameter, an increase of 100% in area.

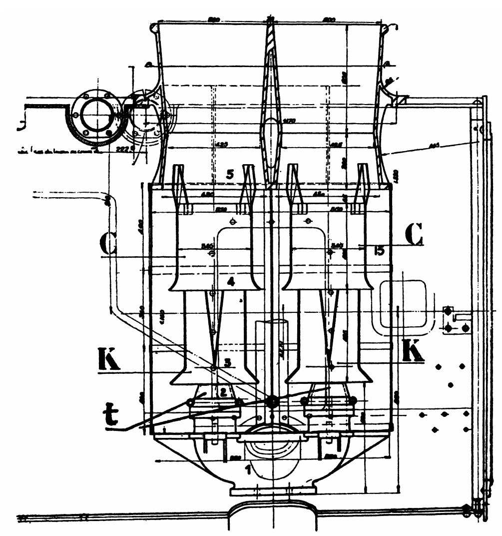


Figure 8 Double Kylchap[11]

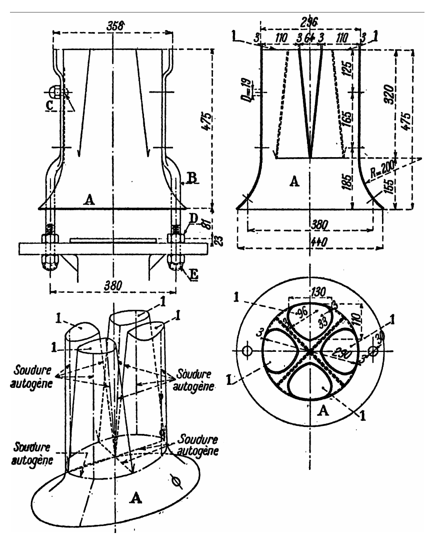


Figure 9 Kylälä cowel[12]

The next development was a patent of the Belgian Lemaître[13]. As described in the patent application his aim was to accelerate the flow in the chimney at the chimney wall.

As a consequence his 6 orifices are directed to the chimney wall and accompanied by a central 7th orifice as shown in Figure 10.

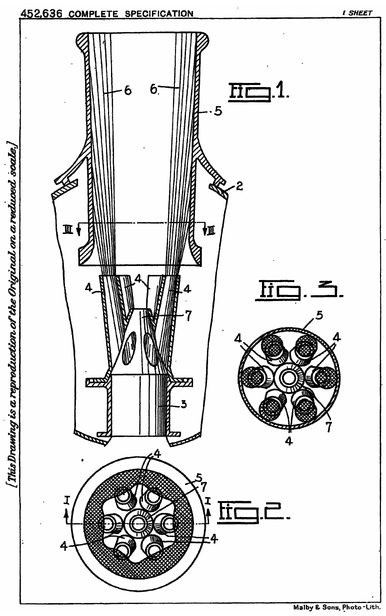


Figure 10 Lemaitre patent drawing[14]

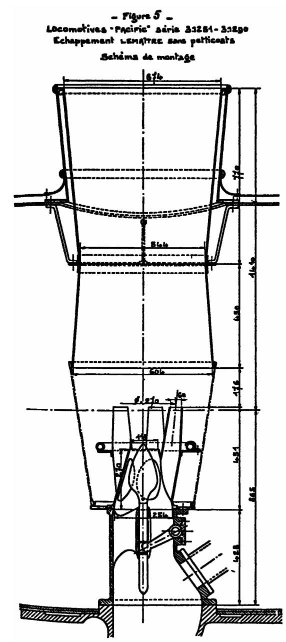


Figure 11 French Nord, Lemaitre front-end[15]

The French Nord developed the concept after extensive testing into a 5 orifice system which also had an adjustable one in the center as shown in Figure 11.

Bulleid of the SR in the U.K. also applied a Lemaître type. His version was apparently based on the perception that a front-end worked on jet entrainment only. As a consequence his orifices were too small, the distance to the chimney too large and the chimney too wide. Of course it was developed into a functional unit. The Merchant Navy Class locomotive “Ellerman Lines”, present in the main exhibition hall of the NRM, shows the unit in the form changed by British Railways after the Rugby tests. However, since the boiler of the MN-class is only 5% smaller than that of the A4-class, the 5 orifices of 2 5/8 inch diameter each, equivalent with one of 5 ¼ inch plus one of 2 5/8 inch, compare poorly with both the 5.5 inch orifices of the Kylchap.

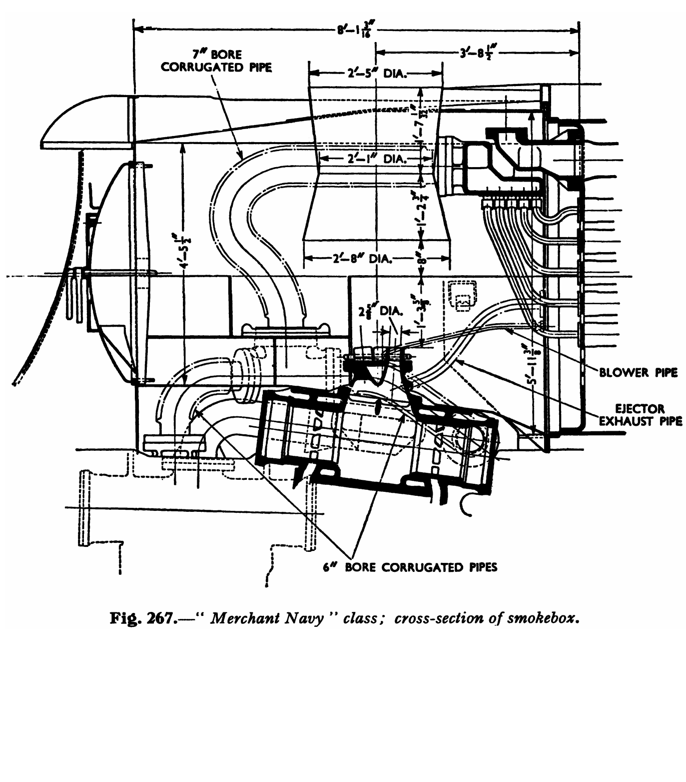


Fig. 267.—*“ Merchant Navy ” class ; cross-section of smokebox.*

Figure 12 Bulleid-Lemaitre front-end[16]

As a curiosity only, Figure 13 shows a front end development in Syria, as published in the Railway Gazette of 1939. It already has some of the features, like wider orifices at both ends of the blast cap, that were patented by Giesl-Gieslingen in 1950.

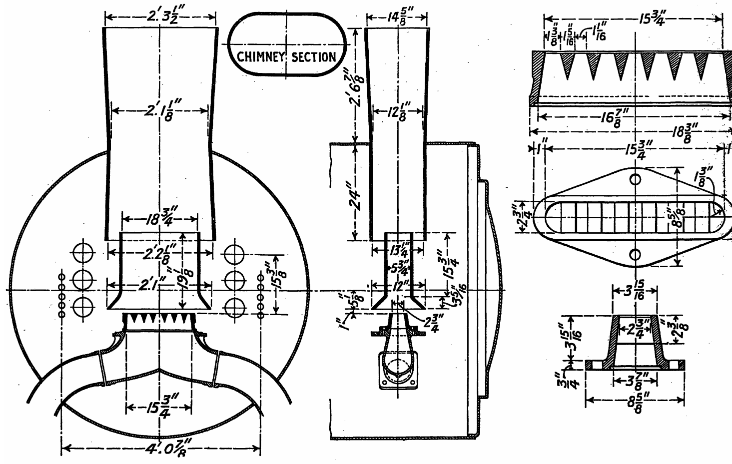
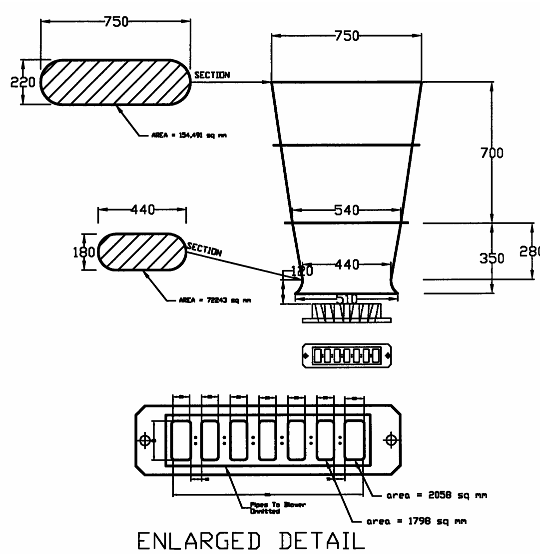


Figure 13 Syrian Railways Godard front-end[17]

After successful testing in Austria, Giesl-ejectors were bought by the British Coal Board for application on some of the War Department 0-6-0 shunters. Figure 15 is a drawing of such a unit. From the drawing can be calculated that the orifice area is some 13000 mm^2, the chimney throat is 72234 mm^2, a ratio of 1:5.5. The chimney throat would be almost as large as that of the standard chimney it replaced.



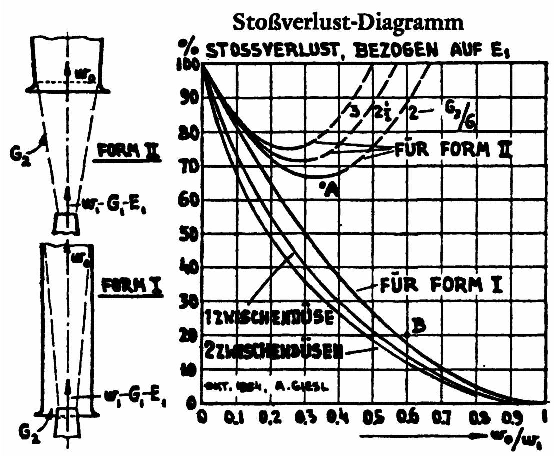
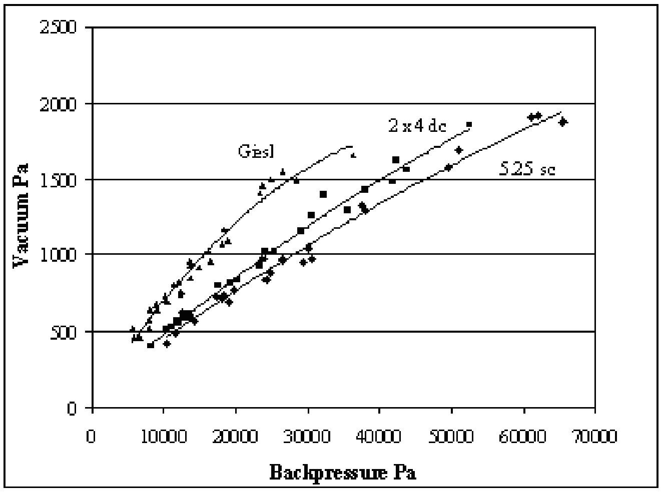


Figure 14 Giesl-Gieslingen shock loss diagram[18]

Figure 15 British Coal Board Giesl front-end[19]

The problem with these ejectors is that they are based on a wrong concept of Giesl. As shown in Figure 14 he thought it possible that the steam-gas mixture could have a velocity of 60%, as shown at point B, of that of the steam. However, if 1 mass unit of steam has a unit velocity, it is impossible to use its momentum, the product of mass and velocity, of 1 to accelerate 2 mass units of gas into 60% of the steam velocity. The momentum would be 3*0.6 = 1.8, which violates the concept of momentum conservation. It cannot be larger than the original unit 1 which would allow only a combined velocity of 33% of the steam. As a consequence, the Giesl units are designed with narrow throats, basically too small, as demonstrated by the results of the BR 9F Giesl tests.



The vacuum curve for the Giesl shows very good performance at the lighter loads but tends to curve to the right at the higher loads. This indicates an asymptotic approach to a limit. This was designed on purpose as described by Slezak in his book on the Giesl Ejector[20]

Figure 16 BR 9F Vacuum-backpressure test results

Very large scale tests were performed by the British Railways between 1953 and 1960. S.O. Ell, who was in charge, published the following Figure 17 showing the preferred dimensions of single and double chimneys. The data of the double chimneys were acquired from the tests with the GWR "King" class locomotives and show that a double chimney system could have a larger orifice area than the equivalent single orifice.

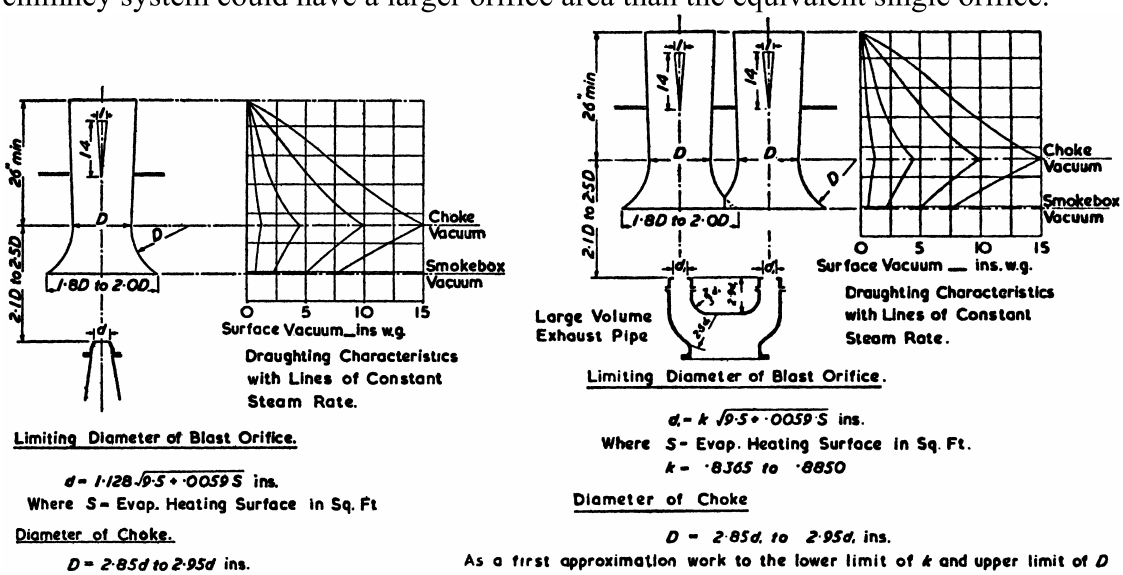


Figure 17 Front-end dimensions according to Ell[21]

The final development is that of the Lempor system by Ing. L.D. Porta from 1957 onwards. The version shown, Figure 18, is that fabricated by Wardale for the SAR 26 class “Red Devil”[22]. This could be regarded as the ultimate development of a classical front-end with multiple orifices and a diffuser chimney.

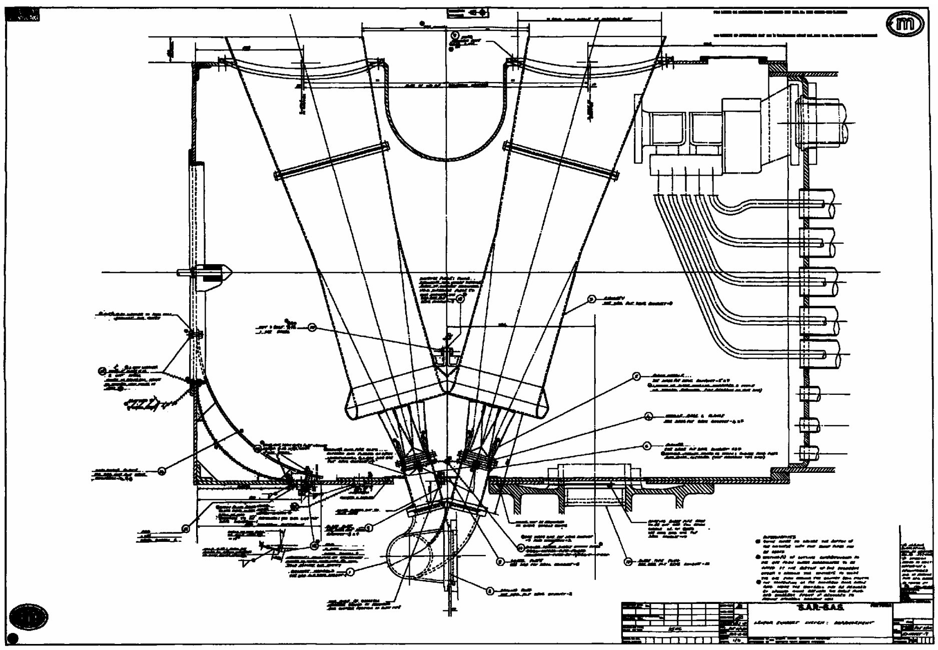


Figure 18 SAR 26 Lempor exhaust system by Wardale[23]

2 Research

To understand the basic principles of the functioning of a front-end some research results will be shown. The first are those of Trüpel[24] in 1912/13. He measured air jet velocity profiles. The wind machine shown in Figure 19 filled an air vessel which had a 90 mm orifice from which air escaped with a velocity of about 90 m/s. For his measurements he used a Pitot type velocity pressure unit which could be moved in 3 dimensions.

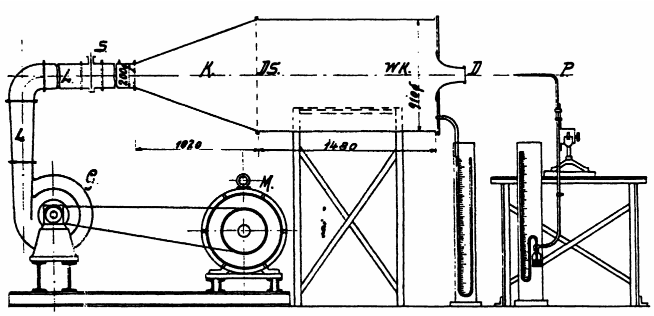


Fig. 1.

Figure 19 Trüpel air jet velocity measurement system[25]

The results are given in the next graph and shown a gradual change in the velocity distribution towards a curve representing a “Gauss” or “normal” type distribution.

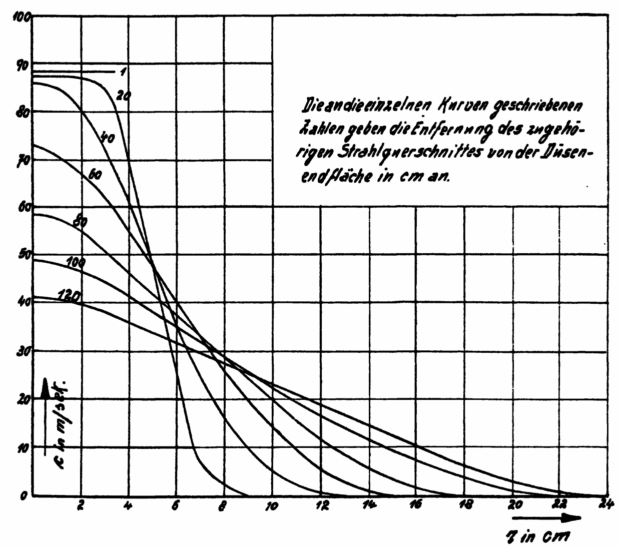


Figure 20 Velocity profiles as measure by Trüpel[26]

The next useful test result is that of the German Wuest[27] in 1950. He used different orifices and catching tubes, making the waterjet a confined jet, and measured the total mass increase at the tube exit.

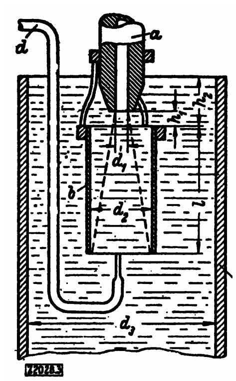
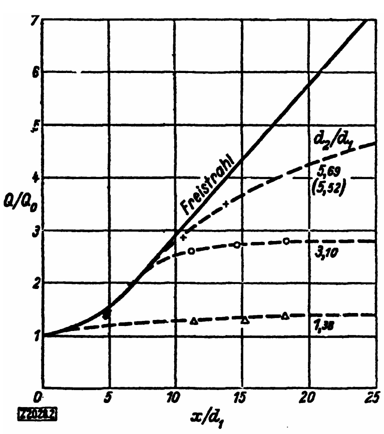


Figure 21 Wuest experimental set-up



The results are shown in Figure 22 They clearly show almost identical results as those of Zeuner: the ratio of total mass Q to that of the driving fluid mass Q_0 cannot be larger than the ratio of the catching tube to orifice diameter would allow for.

Figure 22 Wuest mass ratio related to distance from orifice[28]

The next step is an attempt to investigate whether it is possible to explain the results from these tests with a simulation. The supposition is that the results are due to systematic redistribution of momentum in such a system. In order to do this in a computerized manner the following steps for an element approach are undertaken:

- subdivide of the jet into concentric flow piper of 1 mm thickness each
- calculate the average momentum of 2 adjacent flow pipes
- repeat the process until a velocity of 0.1% of that on the axis is calculated
- regard this as jet boundary and repeat

During the symposium a simulation demo was shown with the Trüpel jet data, a 90 mm orifice issuing air at 88 m/s into a catching tube with a diameter of 270mm.

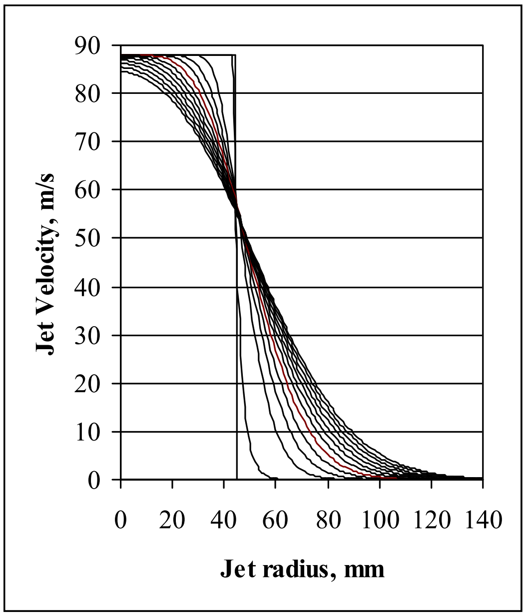


Figure 23 Velocity profiles, mass ratio=1.8

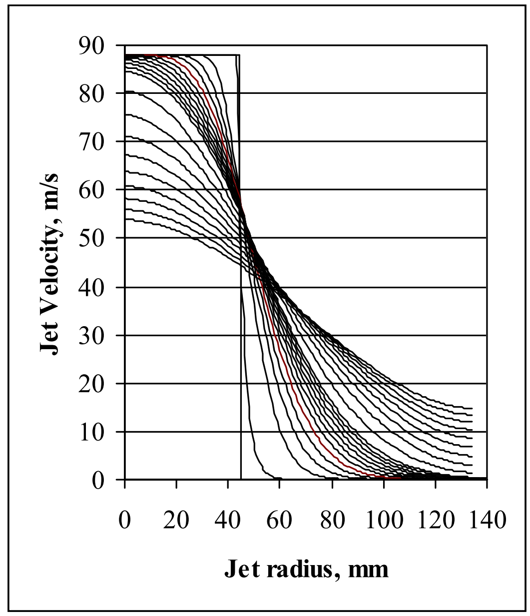


Figure 24 Velocity profile, mass ratio= 2.8

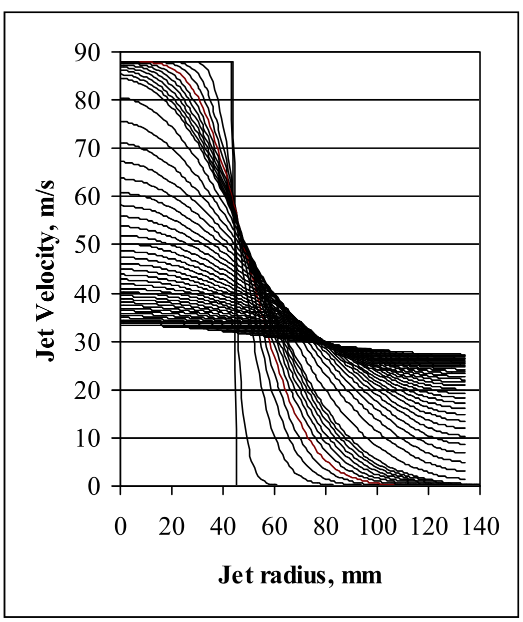


Figure 25 Velocity profiles, mass ratio =3.02

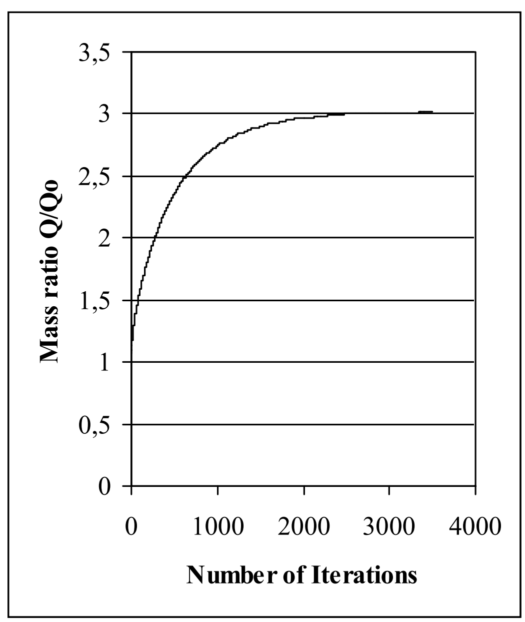


Figure 26 Mass ratio increase

The results are shown here as a series of momentary snapshots, Figure 23 shows the velocity profiles generated at the moment when the jet enters the chimney. The next Figure 24 shows the development within the chimney and the last Figure 25 shows profiles until the iteration where no practical mass ratio increase is shown anymore. Figure 26 shows the ever increasing mass ratio with the number of iterations.
The observations of this process are now:

- The velocity distribution calculated will develop into a "Gauss" or "normal" type distribution. This conforms to the Trüpel measurements.
- The mass flow ratio Q/Q_0 increases systematically towards a limit which is defined by the catching tube to orifice diameter ratio shown in Figure 26. This conforms to the Wuest test results. The simulation stops at that instance.

Since these results are so close to the observations of the historical test results, at least part of the assumptions of the simulation is correct. However since the catching tube does not allow mass increase from the sides, all mass flow must pass the throat to give any mass increase at all. The major conclusion from this exercise is that:

a catching tube/chimney has a sucking action,

if these results are regarded as representative for a parallel chimney system.
However, this aspect was neglected during the simulation, so the final conclusion should also be that it is too simplified.

From the simulation it should be clear that a longer chimney allows for a better velocity profile development which increases the mass flow. A parallel chimney has a limit because the final flat velocity profile cannot be developed any further. A tapered chimney does allow for an increase of this effect for an identical chimney length and, in theory, there is no limit.

The next step is to investigate the dimensions of the hardware within the smokebox that should force the flow into proper behaviour. Correct ratios of these dimensions, the importance of which were defined by an application of the Buckingham theorem[29] for dimensional analysis, will result in a proper functioning front-end. This was demonstrated in the Ph.D thesis[30] using the modified Zeuner equation for tapered chimneys and comparing the calculated results with those of the BR Rugby tests. A simple factor analysis, sorting the results and correlate them with the dimensional ratios of the front end gives the following preferred results:

- Chimney throat / Orifice diameter:	2.9 to 3
- Orifice to throat distance / Orifice diameter:	6 to 7
- Chimney length / Throat diameter:	> 2

However, since it should be understood now in what manner a front-end system functions, it also opens the way to improvement:

- Orifice shapes could be improved
- The taper of the chimney could be increased
- However, this has a practical limit, the flow detaches from the chimney wall
- Also, a diffuser chimney needs a fully developed entrance flow
- Multiple orifices could be applied.

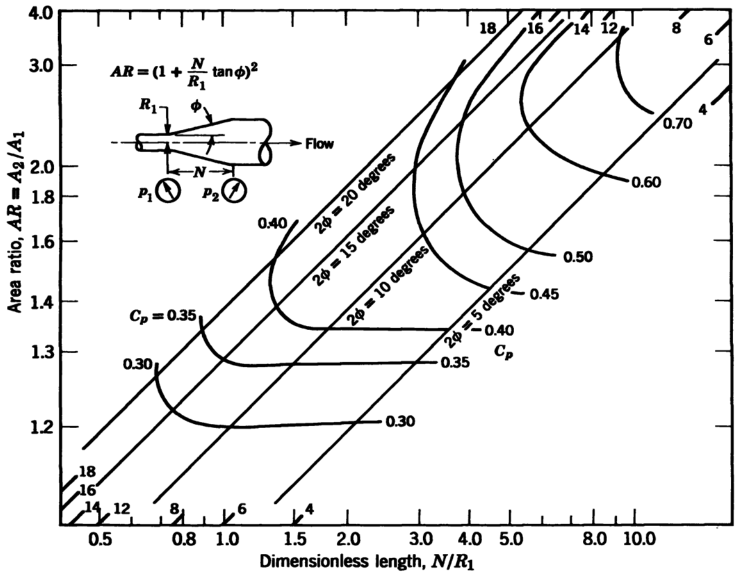


Fig. 8.18 Pressure recovery data for conical diffusers with fully developed turbulent pipe flow at inlet. (Data from [10].)

Figure 27 Diffuser pressure recovery coefficient, Fox[31]

As shown in Figure 27, from Fox, the figure is valid only for fully developed entrance flow, meaning that the diffuser should have a parallel throat section and (multiple) orifices allowing for a uniform velocity profile on entrance of the diffuser. From the figure it is also clear that the diffuser angle has a limit of about 10.5 degrees for shorter diffusers. The figure also shows that the diffuser angle should be reduced for larger lengths. At a length ratio of 8, the angle is already reduced top about 7 degrees if optimal performance is desired.

The next step to improvement is the application of multiple orifices. So the question: *"Why do they work?"* needs an answer.

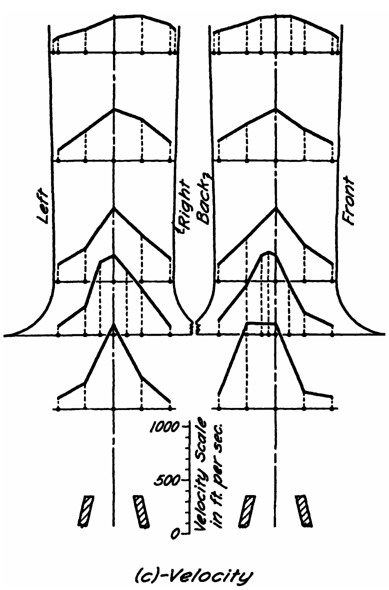
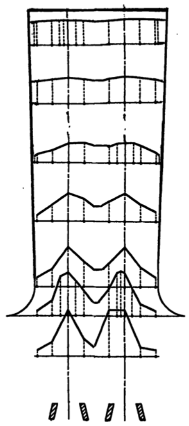


Figure 28 is taken from Young[32] and shows the measured velocity distribution, in two directions, of his 1:4 front end model. It shows the same type of velocity distribution development as discussed earlier.

Figure 28 Velocity distribution in 2 directions according to Young[33]



If this figure is scaled to ¼ area scale, ½ length scale, it is possible to assemble a picture of 4 orifices cooperating with the same chimney, Figure 29. For each of the 4 jets the identical velocity distribution is developed with the first half length of the chimney, allowing for further velocity redistribution and a flatter profile in the next half length.
Since this way of scaling gives exactly the same jet boundary area for both cases, it should be clear from this explanation that, against popular belief, it is not the area of the jets that cause the improved performance.
It is only the length of the chimney which is used in a more efficient manner.
This approach is one of the possibilities of improving a front-end without changes to the chimney.

Figure 29 Velocity profiles of 4 orifices in an identical chimney

However, it should be realized that in this example the boundaries of the jets within the chimney are parallel. So, if the chimney can be changed, another one with *larger taper and inclined orifices* can be applied, allowing for "tapered velocity development" within the chimney for each of the jets.

3 Tests

Since 1999 front-end test have been made on the RTM narrow gauge railway based in Ouddorp, the Netherlands. The 1999 test were made with 0-6-0 type locomotive RTM 56 to investigate the possibilities and to define the performance of the locomotive before restoration and reboilering. It used to have a 65 mm circular orifice. During the tests it appeared it could do with an 80 mm orifice. For these tests a 4-fold blast cap was fabricated with orifices that could be changed from 40 to 50 mm each. The 4 x 40 mm orifices had the same area as the single 80 mm but performed more or less as a single 65 mm orifice. The 4 x 50 mm orifices showed that they were capable of being used under all service conditions with the advantage of having the smallest blast pressure of all.
Since 2003 test have been made with the fully restored and reboilered sister locomotive RTM 54. The earliest aim for this locomotive was to define a proper orifice for the locomotive. The tests confirmed the earlier results and gave the final values for vacua and blast pressures. The locomotive now runs with a circular 80 mm orifice.
In November 2006 the test were rerun with additional blast caps, one with a square opening with Goodfellow projections, the other one with the "projections" rotated outwards. Since these blastcaps were mounted bluntly they appeared to give a higher blast pressure than the circular orifice which had the same area.
Figure 30 shows the different orifices and caps used, from left to right:
The standard 80 mm blast orifice, blastcap with square orifice and Goodfellow projections, square orifice with outside projections, blastpipe and –cap with 4 x 40 mm orifices mounted in place.

Figure 30 Photo of the different orifices

Figure 31 Blast pipe with 4-orifice blast cap

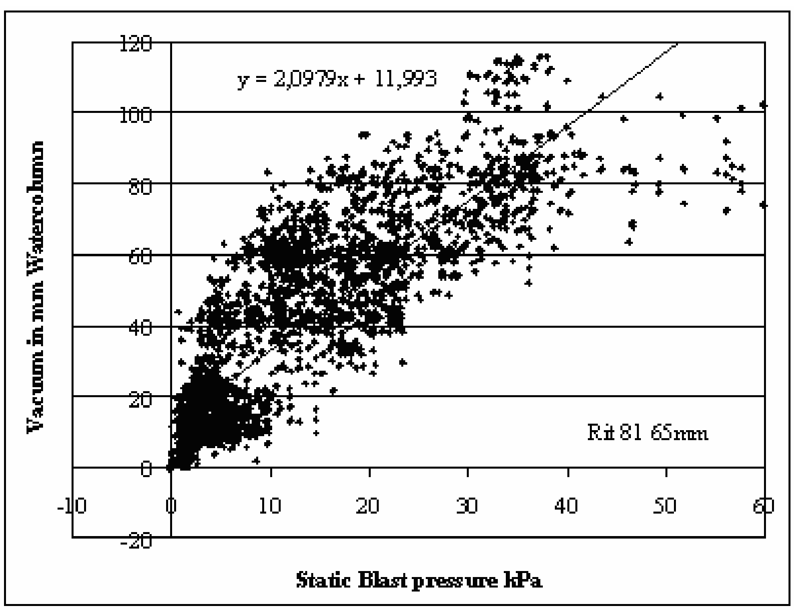


Figure 32 RTM 54 test, results of the original 65 mm orifice

Figure 32 shows the results of one of the tests with a 65 mm orifice. The horizontal scale shows the static blast pressure in kPa as measured in the blast pipe. The vertical scale shows the vacuum measured in the smokebox in mm watercolumn. All measured data of the test are given, showing a high blast pressure and a lot of scatter. The graph also shows that the 65 mm orifice is too powerful, a lot of data is concentrated in the left bottom corner, showing that the locomotive was carefully driven to prevent spark throwing.

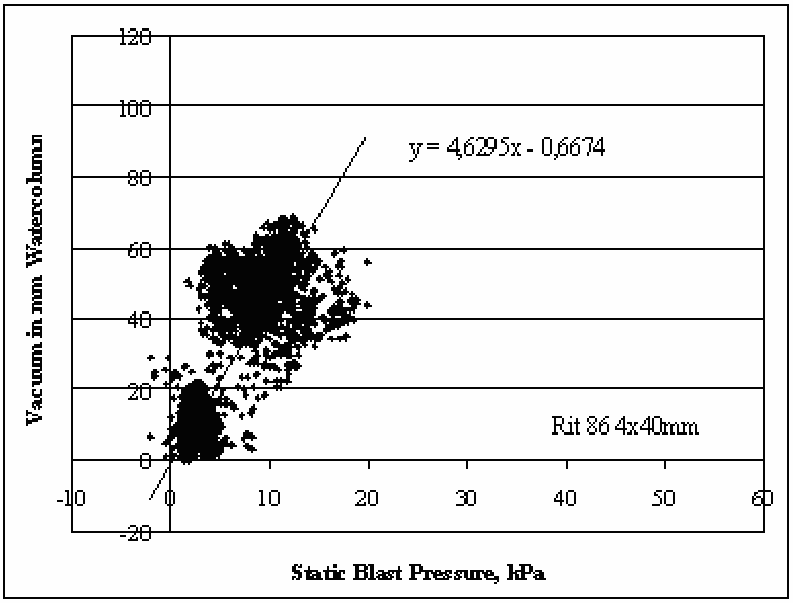


Figure 33 RTM 54 test, 4 x 40 mm orifices

Figure 33 shows the results with the blastcap of 4 x 40 mm orifices. Compared to the earlier test the blast pressure has been diminished. However, the locomotive was still being carefully driven, since the vacuum generated was too high.

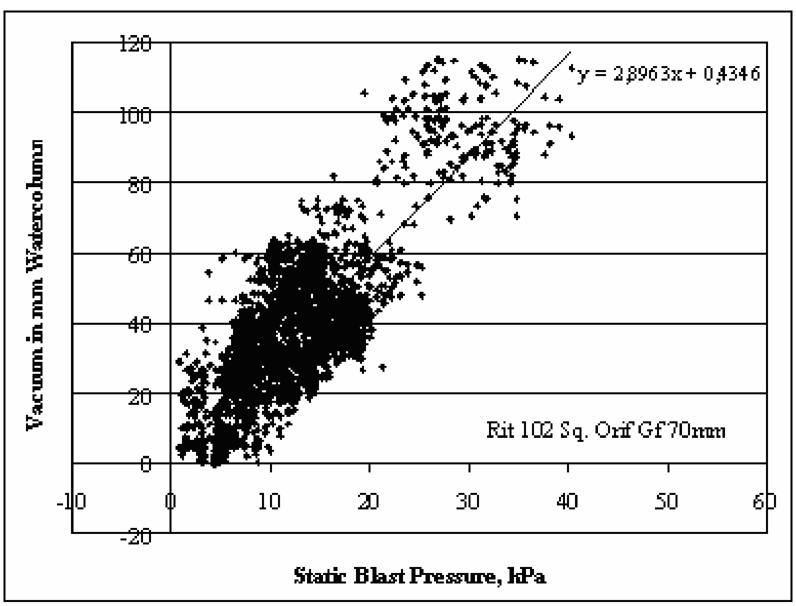


Figure 34 RTM 54 test, square orifice with Goodfellow projections

Figure 34 shows the results of the square orifice, this has the same area as the circular 80 mm one. It shows a blast pressure which is down to about 20 kPa in general.

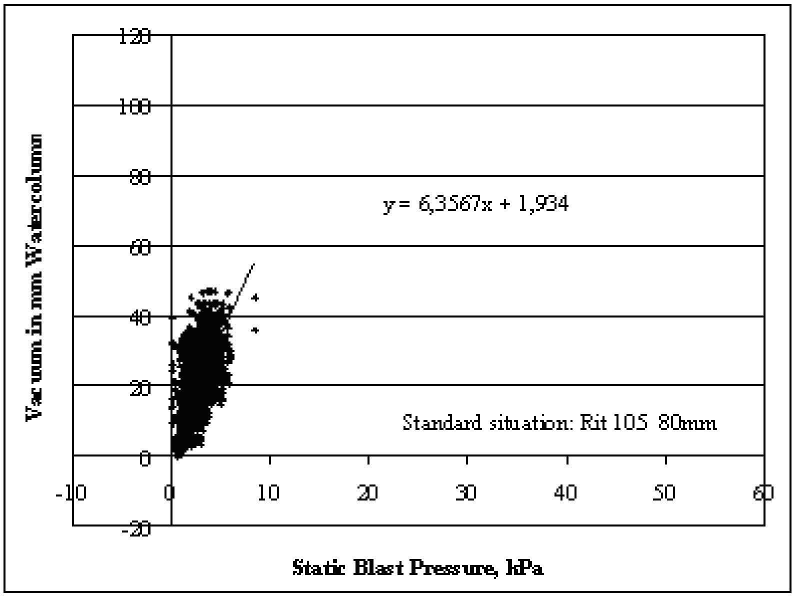


Figure 35 RTM 54 test, standard circular orifice of 80 mm

Figure 35 shows the now standard working condition, the locomotive with its 80 mm blast orifice. The test was made at the end of the working day with a low vacuum needed. The graph shows that the blastpressure is kept within 5 kPa.

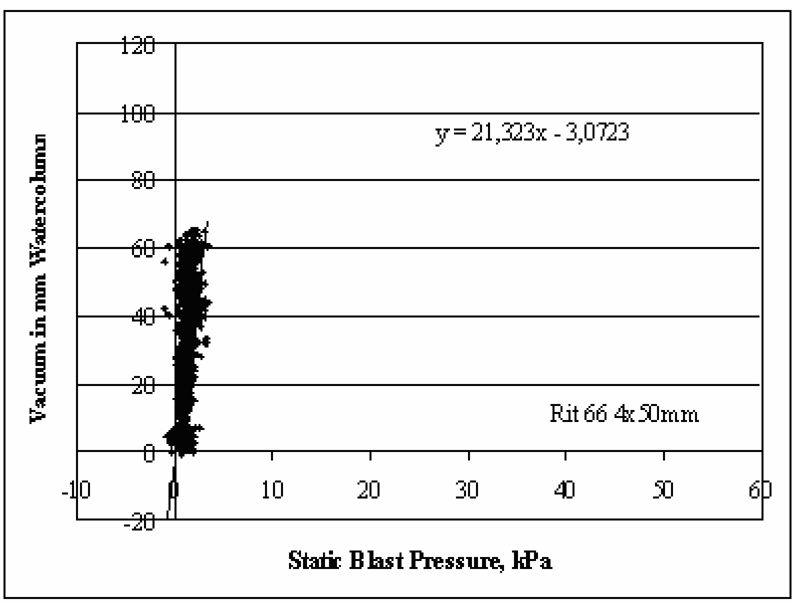


Figure 36 RTM 54 test, 4 x 50 mm blastcap

However, the best results were acquired with the 4 x 50mm blastcap, Figure 36. The total orifice area of the cap was the same as that of the blastpipe. The only static blastpressure left is that of friction in the pipe and cap. The results show that the 60 mm watercolumn of vacuum that the locomotive needs as a maximum does not give any problem.

This last test could be regarded as proof of the earlier assumptions on the function of the chimney: a better velocity distribution increases mass flow and hence the vacuum. The orifice area could be increased from that of an orifice of 80 mm to one of an equivalent of 100 mm without any sacrifice to locomotive performance.

4 Conclusion and Recommendations

Any steam locomotive can have its front-end improved.

The dimensional ratios of the front-end should be checked
and
A multiple orifice blastcap should be applied.

References

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