Feasibility of using low pressure steam for sootblowing

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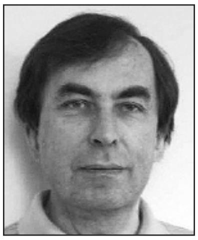

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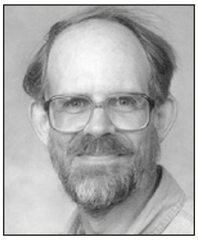

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Abstract: With correctly designed fully-expanded nozzles, the sootblower steam pressure in recovery boilers can be reduced from 300 psig (20 bars) to 150 psig (10 bars), without significantly reducing the deposit removal efficiency. Results of laboratory tests show that a 20% increase in sootblower steam flow can make a low pressure nozzle (150 psig) more effective than a 300 psig nozzle. Since low pressure steam can be extracted from downstream of the steam turbine, it is a less expensive source of steam for use in sootblowing.

SOOTBLOWERS ARE USED to remove fireside deposits from heat transfer surfaces in recovery boilers. Effective sootblowing is vitally important for achieving a high boiler thermal efficiency, and for extending boiler runtime between plugging shutdowns. It is an expensive operation, since sootblowers typically consume 5 to 12% of the high pressure steam produced by the boiler.

Due to high energy costs in recent years, alternative sources of steam for sootblowers have constantly been sought. One such source is the relatively low pressure steam, 150 to 300 psi, from a steam turbine. The main advantage of using this source of low pressure steam is that it is much less valuable than high pressure steam entering the steam turbine. The economic gain is primarily due to the increase in the additional electric power generated by passing the feed steam at high pressure through the turbine generator before it is used for sootblowing.

The ability of a sootblower to remove deposits is closely related to the peak impact pressure (PIP) of the sootblower jet. If low pressure sootblowers are to be used, they must have a cleaning power comparable to high pressure sootblowers. This can be accomplished with the use of larger, fully-expanded nozzles that have been modified to achieve optimum performance at a lower pressure. Since low pressure steam is much less expensive than high pressure steam, the adverse effect of the lower pressure on cleaning power can be compensated for by increasing the steam flow through larger nozzles.

This paper discusses the thermodynamics of sootblower steam, the technical and economical feasibility of low pressure sootblowing technology, and the results of laboratory experiments that have been conducted to evaluate the performance of high and low pressure sootblower nozzles.

SOOTBLOWER THERMODYNAMICS

In a standard sootblower configuration, Fig. 1a, high pressure steam from the recovery boiler passes through a poppet valve to reduce the steam pressure to 250-350 psi before it enters the sootblower lance. In an alternative sootblowing arrangement, low pressure steam (150-300 psi) may be taken directly from the low pressure side of the steam turbine, as shown in Fig. 1b.

At low pressure, some of the sootblowing seam may condense. The condensation occurs because the steam, after being used in the steam turbine, has not only a reduced pressure, but also a lower temperature. After passing through a sootblower nozzle, this low pressure steam may be cooled to below the dew point as it adiabatically expands. The presence of condensation may be determined on the basis of sootblower steam thermodynamics.

Figure 2 shows the thermodynamic variables of sootblower steam presented in an entropy/enthalpy (Mollier) diagram. Steam temperature, pressure and moisture content are shown as parametric lines and are uniquely determined by enthalpy and entropy. The entropy/enthalpy diagram is useful, because many of the processes taking place as the steam passes through the circuit are approximately adiabatic (constant enthalpy) or isentropic (constant entropy), and are represented on the diagram as horizontal or vertical lines respectively.

Steam flow through a pressure reducing poppet valve is essentially adiabatic because there is no significant heat exchange or work done in this process. For a boiler producing 61 bar, 440°C (900 psi, 825°F) steam, properties are shown at point A in Fig. 2. After the poppet valve reduces the steam pressure to 20.4 bar (300 psi), the steam properties lie at point B.

Steam flow through a fully expanded nozzle is almost isentropic, and may be represented in the diagram as a vertical line extending from the lance pressure to the ambient pressure (1 bar = 14.7 psi), as is shown by the line BX, Fig. 2. Point X corresponds to a jet steam moisture level of 4%. In reality, since a sootblower nozzle is not 100% efficient, the steam expansion is not completely isentropic. Hence, the lines representing steam expansion in real nozzles will deviate to the right, corresponding to an entropy increase. As a result, the jet moisture content will be slightly lower than 4%.

Consider now a recovery boiler with sootblowers operating on low pressure steam. In the simplest arrangement, steam from the boiler at 900 psi is directed to the steam turbine where its pressure is reduced to 150 psi, after which the steam goes to the sootblowers. In this case, if the turbine

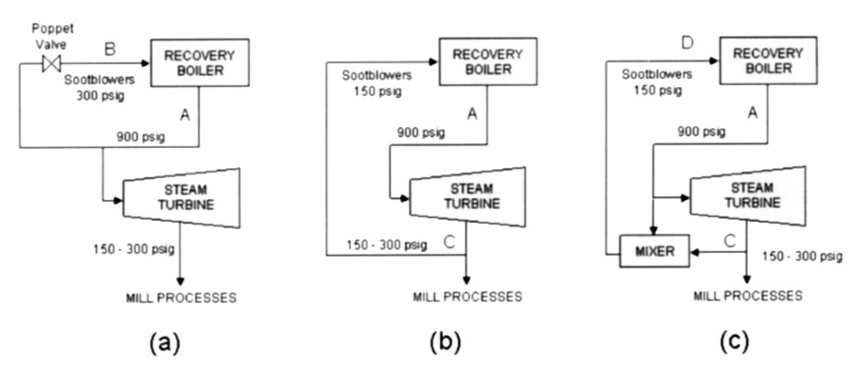

FIG. 1. The supply of sootblower steam: a) standard high pressure arrangement; b) low pressure sootblowing; c) mixing of low- and high pressure steam.

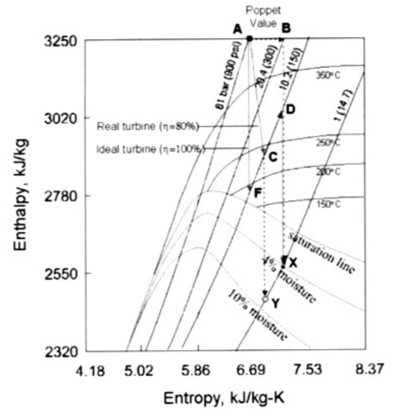

FIG. 2. Mollier diagram for sootblower steam.

is 100% efficient, the steam enthalpy will be converted into electricity isentropically, this process is represented by the vertical line AF in Fig. 2.

In reality, neither the turbine nor the nozzle will be 100% efficient. Hence the steam expansion deviates from isentropic. For a typical turbine efficiency of 80%, the reduction of steam enthalpy in the turbine will be 0.8 of that for an ideal turbine. As a consequence, in the real turbine the path deviates from AF and ends instead at point C on the same isobaric line (P=150 psi) as F, Fig. 2. If this steam then expands isentropically through a full expansion nozzle, it will exit into the boiler at P=1 bar, with steam properties defined by point Y. In this case steam contains about 8% moisture.

This analysis indicates that the moisture content in the low pressure (150 psi) steam jet is higher than in the high pressure (300 psi) jet. This happens because the temperature of the steam at the exit of the turbine, point C in Fig. 2, is lower due to of the energy that has been extracted by the turbine. Complete expansion of this steam in the sootblower nozzle causes its temperature to drop well below the dew point. However, it is possible to raise the steam temperature by mixing it with a certain amount of high pressure steam, as shown in Fig. 1c.

Using the Mollier chart, it is possible to determine the enthalpy required to bring this post-turbine steam to the same isentropic line BX on which the high pressure sootblower operates, i.e. from point C on the line AY to point D on the line BX in Fig. 2. If a low pressure sootblower operates with this conditioned steam, the resulting moisture content at the exit of a low pressure nozzle will be the same as that for the high pressure nozzle (about 4% moisture for an ideal isentropic nozzle). Hence, it is apparent that high-temperature steam can be used to condition the post-turbine steam to prevent extra condensation. On the other hand, it may also be possible to use the higher moisture content of the unconditioned steam.

It is worth mentioning that the erosive effect of condensate in the jet from low pressure sootblowing may not be significant. Heterogeneous steam condensation results in extremely small droplets, less than 0.1 micron [1]. These droplets have very little inertia and thus would not cause tube erosion. Besides, since the low pressure jet has a lower initial velocity, condensation droplets in this jet are accelerated to a lower velocity and the erosive effect of larger droplets would be reduced in comparison to similar droplets in a high velocity jet.

ECONOMICS

The basic economic advantage derived from using low pressure steam for sootblowing arises from the additional electric power generated by passing the high pressure steam through the generator turbine before it goes to the sootblowers. A complete economic analysis would require a thorough steam, heat and electrical balance for both standard and low pressure cases. The exact economic benefit will depend on mill configuration, cost of purchased electricity and fuel, and on other factors. The analysis presented below is preliminary and intended only to estimate the magnitude of possible economic benefits from low pressure sootblowing.

If post-turbine steam is used directly for sootblowing, without concern for condensation, then all the high pressure steam which was used for sootblowing may first be used for the generation of electricity. In this case, the additional generated electrical power W is:

$$W = P/G \tag{1}$$

where P is the high pressure sootblowing steam consumption, G is amount of steam required to generate 1 kWh. It can be easily calculated, using Fig. 2 or steam property tables, that G=10 kg for 150 psi turbine extraction pressure and G=15 kg for 300 psi extraction pressure.

The economic effect may be estimated by assuming a value of $50 MWh for the generated power. Figure 3 shows the economic effect of using low pressure sootblowers as a function of sootblowing steam consumption. No cost has been assigned to the additional low pressure steam required for low pressure sootblowing.

The top line in Fig. 3 shows the economic return that would result if all sootblowers were to be converted to the direct use of 150 psi turbine extract steam. Since it is unrealistic to deliver this pressure to the sootblower nozzles (see "Pressure drop in pipes" section later), the economic return was calculated also for 300 psi extract pressure and presented in Fig. 3 by the thick lower line. Figure 3 shows the economic return that would result if all sootblowers were to be converted to the direct use of low pressure steam. If only some of the sootblowers were switched, then the effect would be proportionally smaller.

As was mentioned above, the use of post-turbine steam for sootblowing causes a decrease in jet temperature. This means that the temperature of flue gases mixed with the sootblowing steam will be slightly reduced in comparison with the standard sootblowing arrangement, as shown by points Y and X in Fig. 2. Therefore, the total steam production capacity of the recovery boiler will be impacted. Calculations show that each additional kilowatt of electric energy produced by using sootblower steam causes approximately 0.3 kW loss in total steam enthalpy produced by the boiler. Therefore, taking into account the adverse effect of lower steam temperature of sootblowers utilizing post-turbine steam will reduce the economic effect by 30% compared to the data presented in Fig. 3. It still, however, will remain significant.

EXPERIMENTAL SETUP

The experimental set-up used to measure jet PIP included a scaled nozzle mounted on a slide, and a Pitot tube with a pressure transducer, Fig. 4. An assembly with two parallel platens could be installed in front of the jet in order to test the effect of

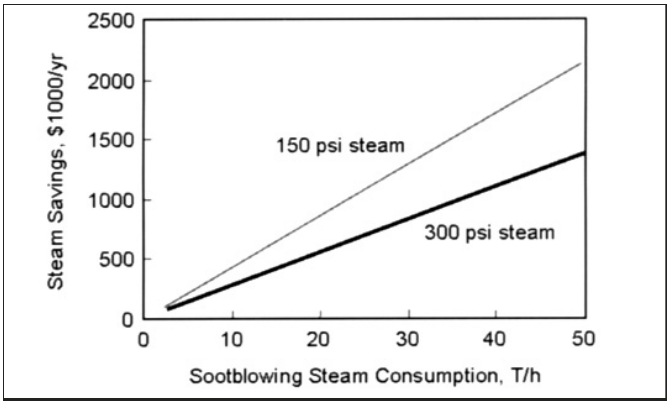

FIG. 3. Economic effect of low pressure sootblowing at $50/MW as a function of sootblowing steam consumption.

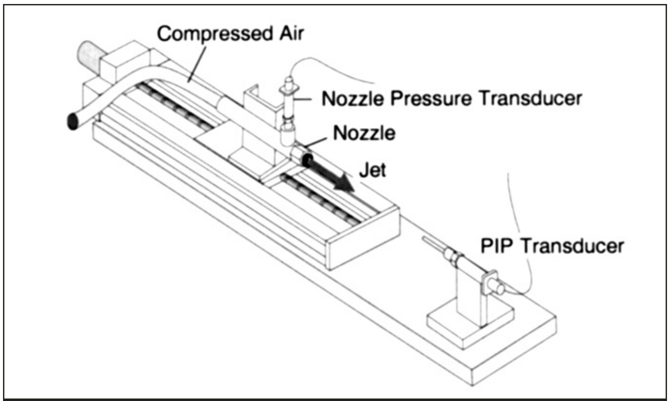

FIG. 4. Experimental setup for measuring jet peak impact pressures.

TABLE I. Geometric similarity and dimensionless groups for industrial 1″ sootblower nozzles and lab nozzle at 300 psi.

	Boiler (300 psi)	Lab (300 psi)
Nozzle exit/throat dia	1.70	1.71
Exit Mach number, *Ma*	2.59	2.61
Jet/ambient gas density ratio, ρ_{ex}/ρ_a	2.25	2.37

platens on jet propagation. The arrangement reproduced the geometric configuration of a superheater section at a reduced scale of 1:4. The inlet nozzle pressure was monitored by a pressure transducer.

In order for the results obtained from the model to be applicable to a recovery boiler, a rigorous set of geometric and aerodynamic conditions must be satisfied for the experimental model. A dimensional analysis shows that not only must the laboratory model and the actual generating bank be geometrically similar (i.e. scaled), but also that the key dimensionless groups for the laboratory and industrial nozzles (Mach and Reynolds numbers) must be equal. Another important parameter which influences jet decay rate is the ratio of nozzle exit gas density to the density of the ambient gas, ρ_{ex}/ρ_a.

The modified laboratory experimental equipment was designed and constructed to achieve close geometrical and fluid mechanics similarity with full scale sootblower nozzles, Table I.

COMPARATIVE PERFORMANCE OF HIGH AND LOW PRESSURE NOZZLES

Two air nozzles were designed and used to investigate the effect of upstream supply pressure and nozzle size on the jet peak impact pressure (PIP). Nozzle parameters were chosen to model, with an air jet, a sootblower steam jet produced at high and low lance pressures. Figure 5 shows the laboratory air jet nozzles and their basic dimensions.

Nozzles A and B were designed to produce fully expanded jets at 300 and 150 psig supply pressure respectively. In order to compensate for the negative effect of lower pressure, the throat diameter of the low pressure nozzle was 7 mm compared to 4.5 mm for the high pressure nozzle. As a result, the flow rate for the low pressure nozzle was about 20% higher than that for the high pressure nozzle.

The measurements of PIP showed that at distances close to the nozzle outlet (less than 10 cm) the PIP of nozzle A was higher, Fig. 6. However, at greater distances, the effect for the larger flow rate of low pressure nozzle B caused the PIP for the low pressure nozzle to actually exceed that of the high pressure nozzle. Not only is the PIP of nozzle B higher at larger distances, but the diameter of the jet is also larger, Fig. 7. In this figure, radial profiles are given for both jets at a distance of 20 cm from the nozzle.

The combined effect of higher PIP and larger jet diameter at the greater distances increases, by a factor of about two, the total force exerted on a deposit by the low pressure jet. Hence its ability to remove deposits at larger distances would be greater than that of the high pressure jet.

The cross-over distance at which the PIP of the high pressure nozzle drops below the low pressure nozzle PIP is all important in establishing the feasibility of low pressure sootblowing. The high pressure nozzle throat diameter in the laboratory tests was 4.5 mm. If we scale up the laboratory experiments to a full-scale sootblower with a 25.4 mm (1 inch) nozzle, the cross-over distance of about 15 cm in the laboratory scales to about 85 cm in the boiler. Hence, provided that the cleaning radius of the high pressure sootblower is larger than 85 cm, the low pressure sootblower is also able to clean up to and beyond this distance, since it has a higher PIP. Therefore, under these conditions, the low pressure sootblower has a larger cleaning radius and may be successfully substituted for the high pressure sootblower. Note that a low pressure sootblower would have nozzles with a throat diameter proportionally scaled to 39.5 mm instead of 25.4 mm.

PRESSURE DROP IN PIPES

The data presented above suggest that it is feasible to carry out sootblowing using low pressure steam from the downstream side of a turbine generator. However, the delivery of low pressure steam to the sootblowers is a challenging problem, which cannot be accomplished using available steam pipe systems. The main reason for this is that the higher flow rate required at the lower pressure causes an increase in frictional pressure losses in the system.

For example, consider a steam flow in a pipe of length L and internal diameter d. Pressure drop Δp may be calculated from the equation:

$$\Delta p = f\,\frac{L}{d}\,\frac{\rho V^2}{2} \qquad (2)$$

where f is the friction factor, (is steam density and V is steam velocity. Since the mass flow rate through the pipe is given by:

$$G = \frac{\pi d^2}{4}\,\rho V \qquad (3)$$

Equation 2 may be presented as:

$$\Delta p = f\,\frac{8}{\pi^2}\,\frac{L}{d^5}\,\frac{G^2}{\rho} \qquad (4)$$

The friction factor f is a function of Reynolds number and tube wall roughness; for the conditions under consideration f is about 0.015.

Equation 4 shows that the pressure loss, Δp, through the sootblower lance increases drastically with decreased pipe

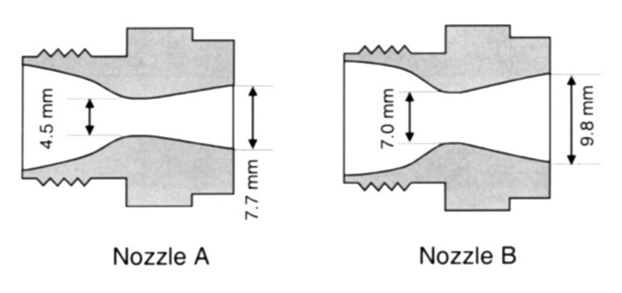

FIG. 5. Fully-expanded air nozzles at different pressures. Nozzle A is high pressure (300 psi). Nozzle B is low pressure (150 psi).

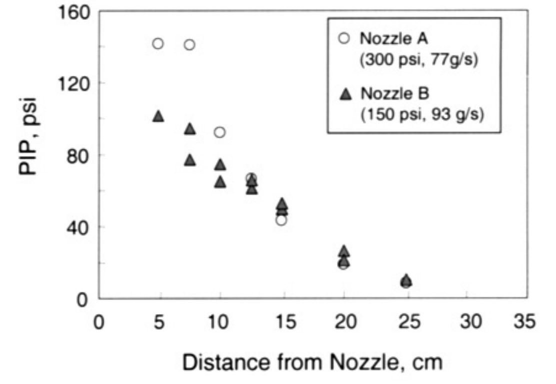

FIG. 6. PIP profiles of Nozzles A and B used in laboratory tests.

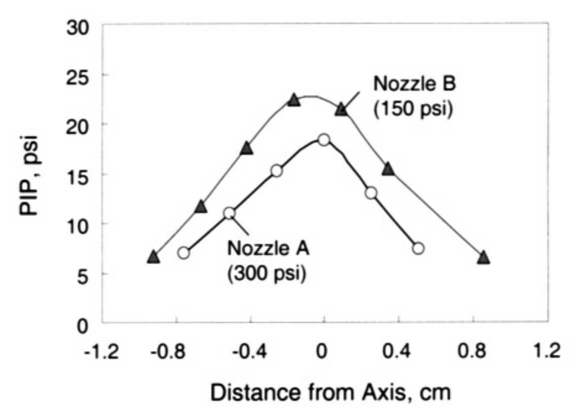

FIG. 7. Radial PIP profiles of Nozzles A and B at 20 cm from the nozzles.

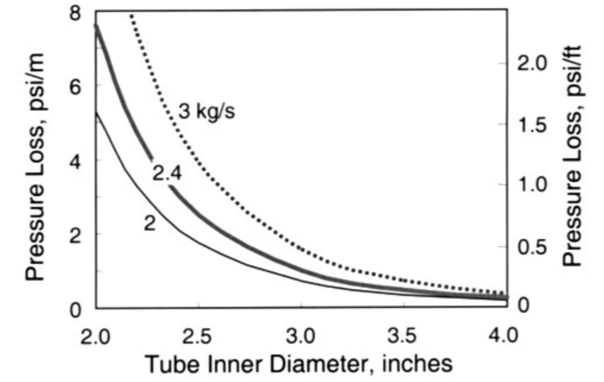

FIG. 8. Pressure loss of 150 psi sootblower steam per tube length as a function of tube inner diameter and steam flow rate (2 kg/s = 15.9 kLb/hr, 2.4 kg/s = 19 kLb/hr and 3 kg/s = 23.8 kLb/hr).

inner diameter, and to a lesser extent, with decreased steam pressure due to the reduction in steam density ρ. The pressure loss also increases with an increase in steam flow rate and pipe length.

Consider a case where a high pressure sootblower (300 psi) with a steam flow rate G of 2kg/s (15.9 kLb/hr) is to be converted to a lower pressure sootblower (150 psi) with a 20% higher steam flow rate, 2.4 kg/s (19 kLb/hr). At 300 psi, a 50.8 mm (2 inch) pipe would cause a pressure drop of 2.6 psi/m (0.8 psi/ft) as the steam passes through the pipe, while at 150 psi, a much larger pressure drop, 7.6 psi/m (2.3 psi/ft), would result. Thus, for a 10 m long pipe that connects an individual sootblower to the main steam line, the pressure loss would be reasonable, 26 psi, for the high pressure sootblower, but would be unacceptably high, 76 psi, for the low pressure sootblower. However, this pressure drop would be substantially lower, only 1 psi/m, if a large inner diameter (76.2 mm or 3 inch) pipe is used. It is clear that at least 3 inch ID steam tubes are required to avoid unacceptable steam line pressure drops for sootblowers operating at 150 psi. Figure 8 shows the pressure loss as a function of pipe diameter for 150 psi sootblower steam at different flow rates.

The majority of sootblowers used in recovery boilers are equipped with 76.2 mm (3 inch) inner diameter lance tubes. Since the sootblower feed tubes are typically 53-58 mm (2.1-2.3 inch) in inner diameter, the pressure loss for a 6 m long feed tube with 2.4 kg/s flow rate will be 30-40 psi. The control valve accounts for another 20-30 psi pressure loss. If a conservative estimate of losses in the supply tube of 10 psi is assumed, and all pressure losses are added, the required pressure at the source should be 60-80 psi higher than 150 psi, i.e. at least 210 to 230 psi.

Therefore, switching to low pressure nozzles requires a steam source of at least 210 to 230 psi. Using lower pressure sources would require the complete redesigning of sootblowers, including larger diameter lances and more expensive “zero pressure loss” valves. This may require substantial capital investments, and thus reduce the immediate economic benefits of using low pressure steam.

CONCLUSIONS

This work has shown that it is feasible to carry out sootblowing using low pressure steam from the downstream side of a turbine generator. With the existing sootblower equipment, the steam pressure at the turbine exit needs to be 210 to 230 psi or higher. Using lower pressure steam requires at least a 3 inch ID pipe to deliver steam to the sootblowers, as well as larger diameter feed tubes.

The operation of sootblowers using low pressure steam could provide significant savings, even though a 20% increase in sootblower steam consumption may be required. This increase in steam flow rate would compensate for the power loss caused by the lower peak impact pressure of the low pressure nozzle operating at the same steam flow rate. Properly designed nozzles with a larger throat diameter are required for effective low pressure sootblowing.

The direct use of low pressure steam from the steam turbine may result in about 4% increase in steam moisture content at the sootblower nozzle exit due to condensation. However, it is possible to avoid this increased condensation by mixing the low pressure steam with a small amount of high pressure steam.

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LITERATURE

1. GORBUNOV V.N. *Nonequilibrium condensation in high-speed gas flows.* Gordon and Breach Science Publishers, New York (1989).

Résumé: Lorsque les tuyères entièrement étendues sont bien conçues, on peut réduire de 300 psig (20 bars) à 150 psig (10 bars) la pression de vapeur des souffleurs de suie dans les chaudières de récupération, tout en continuant d'éliminer les dépôts de manière efficace. Les résultats des essais en laboratoire ont démontré qu'une augmentation de 20 % du débit de vapeur peut rendre une tuyère basse pression (150 psig) plus efficace qu'une tuyère de 300 psig. Puisqu'il est possible d'extraire la vapeur basse pression dans le circuit en aval de la turbine à vapeur, cette source de vapeur moins chère peut être utilisée pour le soufflage de la suie.

Reference: KALIAZINE, A., CORMACK, D.E, TRAN, H., JAMEEL, I. Feasibility of using low pressure steam for sootblowing. *Pulp & Paper Canada* 107(4): T80-84 (April, 2006). Paper presented at the 2004 International Chemical Recovery Conference in Charleston, SC, June 6-10, 2004. Not to be reproduced without permission of PAPTAC. Manuscript received September 06, 2004. Revised manuscript approved for publication by the Review Panel on July 28, 2005.

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