Technical Report

Application of steam in the glass forming process

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1. Introduction

In the glass container forming process the heat withdrawal from the glass is a machine-speed limiting parameter. Together with the heat transfer between the mould and glass, further applied cooling to the glass melt is achieved through the introduction of the blowing medium (air). Whilst the limitations of heat transfer by cooling the moulds are reached, the opportunities to withdraw heat from the inside side wall surface of a container are only partially used. In a newly applied process the conventional blowing medium of air is replaced with superheated "dry" steam. This should enable a significant increase in productivity without involving great modifications to the IS machine.

2. Why steam?

Steam has different physical properties compared with air, which influence the ability to absorb heat by convective and radiative heat transfer (table 1). The specific heat capacity of steam at 150 °C is more than twice as high as that of air at 25 °C.

In addition steam has a significantly lower density, which when compared at a constant blowing pressure is responsible for a greater volume flow/speed travelling through the object to form.

$$\dot{Q}_K = \alpha \cdot A \cdot \Delta T \,. \tag{1}$$

Both aspects significantly influence the heat removal process from the glass melt by convective heat transfer. The influence of the physical parameters stated in table 1 enter the heat transfer equation (1) to determine the heat flux Q from the glass into the gas which is defined through the heat transfer coefficient α, the temperature difference ΔT and the glass surface A in contact with the blow media. Both density and heat capacity are factors directly linked with the heat transfer coefficient α.

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Table 1. Physical properties of air and steam at 1 bar absolute [1]

	air at 25 °C	steam at 150 °C
density in kg/m^3	1.168	0.5164
specific heat capacity in kJ/(kg K)	1.007	1.980
thermal conductivity in 10^{-3} W/(m K)	26.06	28.5
thermal diffusivity in 10^{-6} m^2/s	22.15	28.22
kinetic viscosity in 10^{-7} m^2/s	158.2	274.6
dynamic viscosity in 10^{-6} Pa s	18.48	14.18

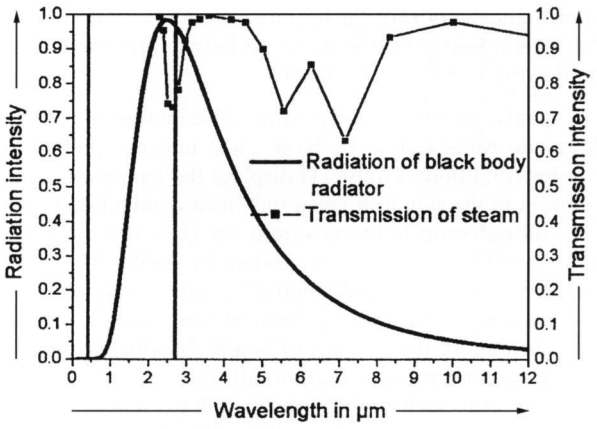

Figure 1. Radiation of black body radiator at a temperature of 900 °C and transmission spectrum of steam (1 bar, 100 mm thickness) in dependence on wavelength.

In addition steam as a higher molecular gas compared to air absorbs more radiated heat during the forming process. Figure 1 shows that the maximum of the black body radiator at 900 °C lies in a minimum of the transmission spectrum of steam. As transmission and absorption are linked, a minimum in transmission will result in a maximum in absorption and therefore contribute to an improved heat transfer from the glass into the gas.

Based on these physical parameters an explanation is available to the early tests/findings [2] where an improve-

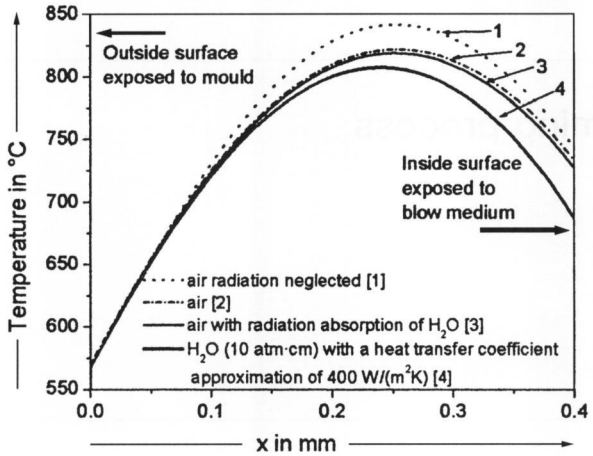

Figure 2. Glass temperature distribution in the container side wall after a 3 s final blow process.

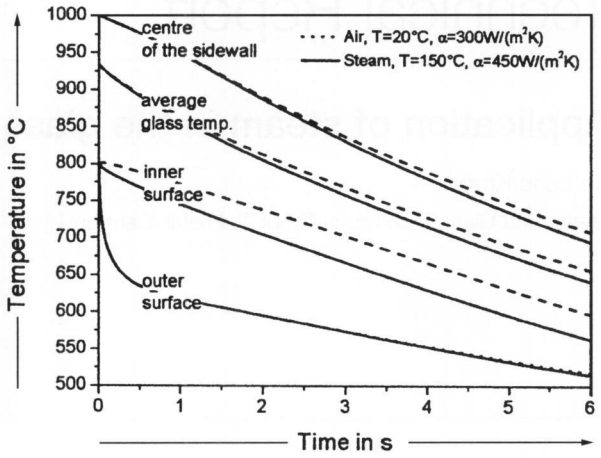

Figure 3. Temperature gradient change whilst blowing.

ment was found in the glass cooling process whilst applying steam as a new final blowing medium.

3. Verification

To gain the proof of the ability of the steam to cool more effectively than air mathematical modelling [3], flow test station experiments and pyrometrical measurements at a full industrial installation were undertaken.

The graphs in figure 2 display the glass temperature distribution of the side wall of a container. This is purely a mathematical model of the heat distribution within the glass melt after a heat withdrawal process between the mould and the flowing gases air and steam.

Figure 2 shows the temperature distribution in a 4 mm glass side wall after a 3 s blow cycle under various heat transfer conditions. Graph (1) displays the temperature distribution in the side wall when only heat conduction is present and radiation influences from the glass volume to the mould and into the gas are neglected. In graph (2) the radiation from the whole glass volume towards mould and blow media is considered. The gap between these two graphs confirms once more the findings of [4 and 5], which stated the importance to consider radiation influences when discussing heat transfer in such applications. Graph (3) states the influence of different absorption qualities. The absorption ability of steam enables a further temperature reduction of 2 to 3 K integral glass temperature. The full cooling ability of steam then becomes visible when the increased heat transfer coefficient is considered (graph 4).

These conclusions have been derived from the previous modelling:

- Only taking into account the absorption of radiated heat when replacing air with steam creates an estimated integral temperature reduction of 2 to 3 °C in the glass.
- Applying a 30 % increased heat transfer coefficient (blowing medium → glass) results in a clear reduction of integral glass temperature.

Through further modelling the heat transfer coefficient for steam could be corrected to 450 W/(m² K). Figure 3 shows the temperature change over blowing time in the glass. The integral glass temperature after the application of several seconds of cooling with steam is significantly lower than after cooling with air. The temperature reduction on the internal glass surface will cause a viscosity increase and will contribute to the geometrical stability of the glass. For a given constant glass temperature the cooling time can therefore be reduced by applying steam as the blowing medium in order to achieve the same final glass temperature as while applying the blow medium air.

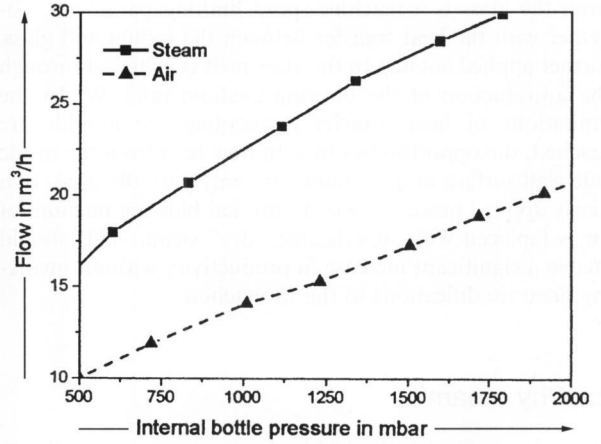

Figure 4. Volume flow rate from a container in reference to the internal bottle pressure.

4. Flow analysis using a simulation test bench

A test station has been designed to investigate and simulate the blowing condition on an IS machine. Using this testing apparatus the flow and pressure situation in the manufacturing process (in a cold environment) was analysed.

It is apparent with steam a far greater volume flow rate is achieved. For different internal bottle pressures steam has a far greater volume flow rate than air (figure 4). This confirms the predicted cooling effect when comparing the

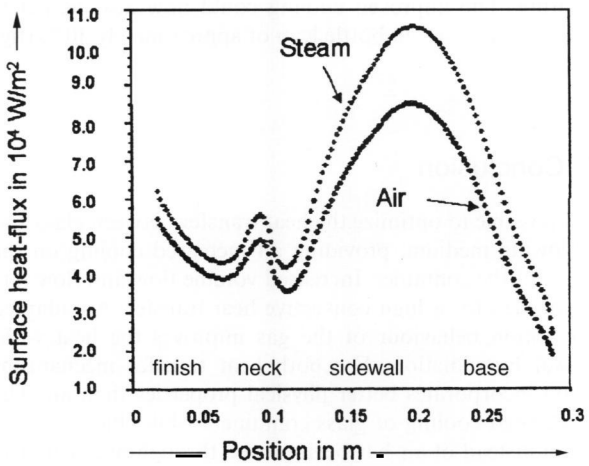

Figure 5. Surface heat flux (W/m²) from the container side wall into the gas.

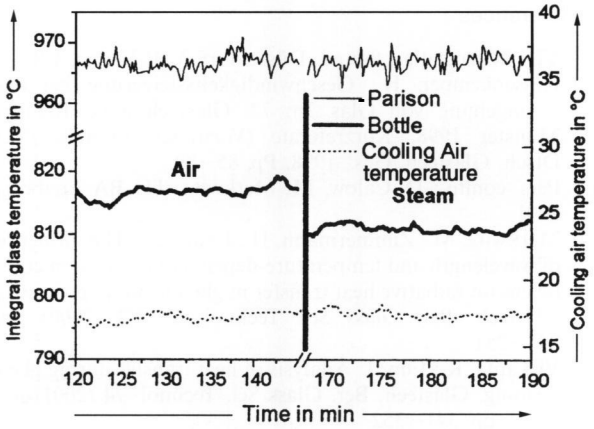

Figure 6. Integral temperature of an 1 l VdF container in the side wall and base area during a production with air and steam, respectively. Further the parison and mould cooling air are displayed.

Table 2. Calculated heat absorption of air and steam in kJ for a 3.5 s final blow

	air	steam
base	0.85	1.12
side wall	24.1	29.2

physical parameter of steam and air for the convective heat transfer (table 1).

5. Mathematical flow modelling profile within a bottle during the forming process

Based on a flow model for the blowing process within a straight-neck flint glass bottle the flow pattern through the container has been determined. Further the heat transfer for air and steam was calculated. For steam a significantly higher heat flux was realized (figure 5). For a typical blow head design and a blowing duration of 3.5 s the heat absorption (table 2) was calculated.

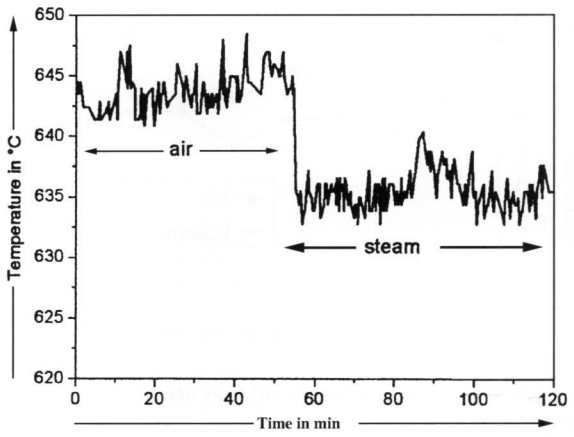

Figure 7. Integral temperature reduction caused by steam in a wide-mouth container (finish).

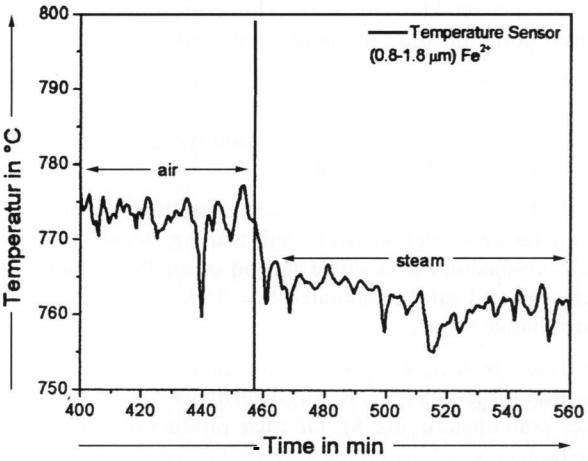

Figure 8. 0.33 l beer container production of 425 bottles per minute with air and steam, respectively. Pyrometer viewing the neck/shoulder area of the container.

Obviously, the cooling effect reaches its maximum where the travelling velocity of the gas is at its maximum. This occurs when the gas travels along the side wall and in the neck. The corners in the base area are very difficult to cool. As a consequence an improved blow head design will improve cooling in areas where the geometrical stability of the glass is achieved the latest.

6. Application to the industrial process

On a 6-section IS machine comparing glass temperature measurements whilst replacing the final blowing medium of air with steam has been performed. After the opening of the finish mould the glass temperature was recorded by several infrared pyrometers[2)], located in various positions and set at various wavelength frequencies. Parallel to this, the mould temperature, mould cooling air temperature and parison temperature were recorded in order to avoid misinterpretations through outside influences (figure 6).

[2)] Temperature measurements in cooperation with Silitec GmbH, Freiberg (Germany).

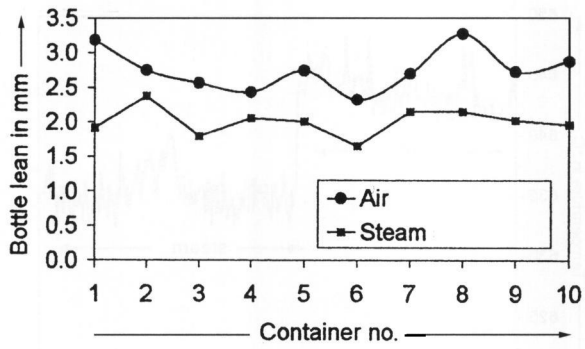

Figure 9. Lean measurement at 165 mm height on a long-neck beer bottle.

By the comparison of a production of 30 min each an integral glass temperature reduction of 5 K was obtained while applying superheated steam at about 150 °C and 2.5 bar pre-set blow pressure. This corresponds to an internal bottle pressure of about 1 bar while forming.

In further investigations using a mobile steam unit various productions have been analysed comparing the use of steam with air on different production types involving other glass colours and glass weights.

In the finish of a flint glass wide-mouth jar a significant temperature reduction whilst substituting steam for air as blowing medium to a single section of an IS machine was achieved and can be estimated to a 15 K integral temperature change (figure 7).

For a blowing time of 0.9 s an integral temperature reduction for steam of 10 K was determined for a green-glass beer container (figure 8). Of each production ten sample containers were taken while keeping a constant parison temperature. The improved cooling could now also be determined as decrease in bottle lean of approximately 30 % (figure 9).

7. Conclusion

It is possible to optimize the heat transfer between glass and a blowing medium, providing an increased cooling on the inside of the container. Increased volume flow and flow rate are needed for a high convective heat transfer. An adapted adsorption behaviour of the gas improves the heat withdrawal by radiation. For both heat transfer mechanisms steam incorporates better physical properties than air. The accelerated cooling of glass containers whilst blowing with steam instead of air has been proved through mathematical modelling and experimental testing in an industrial environment.

8. References

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