Original Paper

Contact between hot glass and wet porous material

Part 2. Trials on a continuously operating container forming machine[1])

Wolfgang Trier[2])

The narrow neck press and blow process for the production of lightweight bottles uses a slender plunger. It is suspected that the plunger decreases the bursting strength and above all the impact resistance of the bottles by damaging the inner glass surface of the parison. It was the aim of the project to develop a "steam plunger" using a wet porous material, which would protect the glass surface by a developing steam layer between glass and plunger.

Trials with different steam plunger constructions show that the production of bottles is possible with this system at normal production speeds. The bursting strength of the bottles produced was a little higher than that of the normal production; the impact resistance remains the same. Steam plungers, permeated by water from the inside, have a tendency to thermal instability. The control of the water penetration is essential. The vulnerable point is the tip of the plunger. The control of the contact temperature of the plunger tip after the loading of the gob is very important.

For the trials stainless steel was used for the plungers. The results show that, especially for the tip region, a material with a high heat penetration coefficient is advantageous. Bronze would be better than stainless steel.

Parallel with the trials, a mathematical model was developed in order to understand better the behaviour of the steam plunger system. The results were in good agreement with the trials.

Kontakt zwischen heißem Glas und feuchtem porösem Material
Teil 2. Versuche an einer kontinuierlich betriebenen Behälterglasmaschine

Beim Enghals-Preßblasverfahren für die Produktion leichtgewichtiger Flaschen wird zur Herstellung des Külbels ein schlanker Preßstempel verwendet. Es besteht der Verdacht, daß durch den Preßstempel die innere Oberfläche des Külbels verletzt und damit die Berstdruck- und vor allem die Schlagfestigkeit des Behälters vermindert wird. Ziel der Arbeit war, durch Verwendung von Preßstempeln aus genäßtem Sintermetall eine Dampfschicht zwischen Glas und Preßstempel aufzubauen, die die Glasoberfläche vor Verletzungen schützt.

Betriebsversuche mit solchen Stempeln zeigten, daß unter Beachtung von bestimmten Konstruktionsmerkmalen für den Stempel Flaschen unter normalen Betriebsbedingungen hergestellt werden können. Gegenüber der Normalproduktion sind die Berstdruckwerte um $\approx 10\,\%$ höher, die Schlagfestigkeit bleibt gleich. Sintermetallstempel, die von innen mit Wasser beaufschlagt werden, neigen zu thermischen Instabilitäten. Besondere Aufmerksamkeit erfordert die Plungerspitze. Hier spielt neben dem Strömungswiderstand des ausströmenden Dampfes die sich kurzfristig nach dem Tropfenfall ausbildende Kontakttemperatur eine wichtige Rolle.

Bei den Versuchen wurden Sintermetalle aus rostfreiem Stahl verwendet. Die Ergebnisse zeigen, daß besonders für die Plungerspitze Materialien mit einer hohen Wärmeeindringzahl benötigt werden. Bronze ist zum Beispiel besser geeignet als rostfreier Stahl.

Parallel zu den Versuchen wurde ein Rechenmodell entwickelt, um zu einem besseren Verständnis der Zusammenhänge zu gelangen. Die Ergebnisse von Rechenmodell und Versuchen stimmten gut überein.

1. Introduction

Part 2 of this paper deals with the behaviour of a plunger of wet porous material in a section of a glass container forming machine operating by the Narrow Neck Press and Blow (NNPB) process. It was intended to develop a "steam plunger", whereby the steam layer developing during the press operation would prevent direct contact between plunger and glass. The aim of this approach was to produce stronger glass containers by avoiding contamination or damage of the inner glass surface of the parison.

2. Construction of a steam plunger

After some previous trials a plunger construction was developed, which is shown in figure 1. The plunger body is made of porous sintered stainless steel (Cr–Ni–Mo, 18/12/2). The pores on the surface, which become partially closed by machining, were reopened by a special surface treatment. The water permeating the plunger from the inside is introduced by a central tube with a single outlet at the top. The tube forms an annular space between plunger wall and itself. The plunger body is welded to a solid base plate. There is an O-ring seal be-

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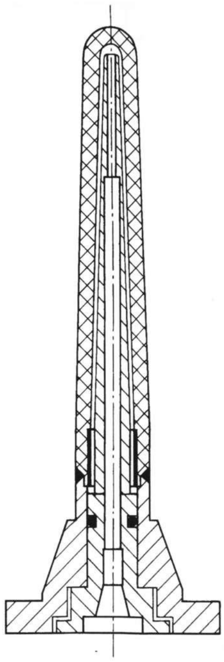


Figure 1. Construction of a steam plunger for the production of a 0.3 l beer bottle by the NNPB process.

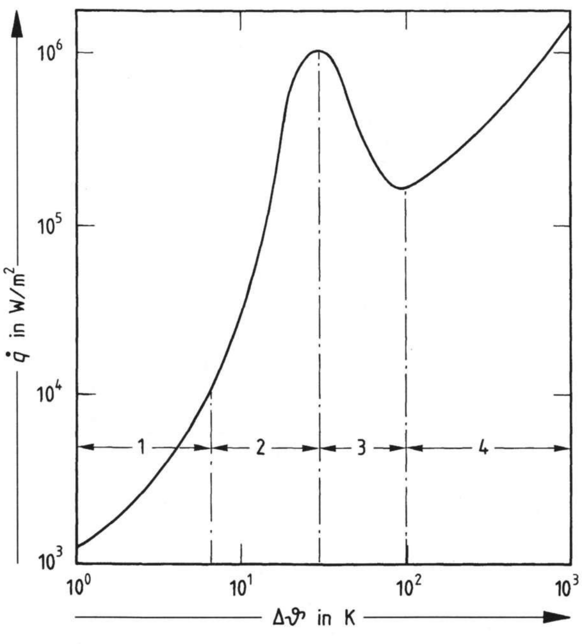


Figure 2. Heat flux density as a function of temperature difference between surface and boiling temperature [2]. 1: convection condition, 2: bubble evaporation, 3: partial film evaporation, 4: stable film evaporation.

tween the tube and the base plate, and a one-way valve is incorporated in the latter.

3. Behaviour of the plunger during operation

The theoretical considerations and the trials in a test rig show [1] that the heat flux density between hot glass and wet porous metal in a tight system over the contact period $0 < t < 1$ s is in the order of $140 \cdot 10^3$ W/m^2. A tight system is defined as one where no steam escapes laterally between the glass and the porous medium. In this case the heat flux density is considerably lower than the heat flux density which is observed for direct contact between glass and solid metal. The heat flux density is here in the order of $800 \cdot 10^3$ W/m^2. With this value it was expected that the parison would be too soft when formed using a normal machine operating cycle.

It was very surprising that, with the same operating timings as the sections with solid air-cooled plungers, the parison produced in the section with the steam plunger showed a normal stiffness in the upper part and a higher stiffness in the finish region.

The water was fed in two separate pulses, one immediately before the loading of the gob and one after reversion of the neck rings. The rate of feed of the water was in the order of 2 to 3 cm^3/pulse. The distribution of the water over the plunger surface was not uniform. In the upper region the distribution was good. The change of colour of the metal surface by the penetration of the water could be readily observed. The second shot showed a very unequal water distribution. In the middle region, the water boiled up locally and flowed down into the neck rings.

The parisons and bottles produced showed a normal glass distribution. The finishes of the bottles showed some small cracks.

To improve the water distribution, a tube was placed on the inside of the plunger near the base plate to prevent the excess flow of water in this region (see figure 1). After this change, the excess water in the finish region was reduced but not eliminated.

The reason for the discrepancy between the heat flux density observed on the bottle machine and that found on the test rig is not understood. Probably there are always system leaks and the steam is able to escape during the glass contact phase. In this case the heat flux density would increase (see [1]). Another point is the strong reboil of the hot water into the developing gap between the glass and the metal surfaces as the plunger retracts. It is well known (figure 2) that local boiling of water induces a very high heat flux density under certain conditions [2].

To achieve a stable operation of the plunger and to produce a good bottle it was necessary to ensure that the porous metal plunger tip was wet before the gob was loaded onto it. If the plunger was dry the glass would stick to it after two or three cycles.

4. Improvement of water distribution

The first trials with the steam plunger in one section of an IS machine showed that the control of the water distribution on the plunger surface, especially in the tip region, is the first requirement for a stable operation. To achieve further improvements it was necessary to obtain a better understanding of the flow conditions in the porous material. In the first approach a one-dimensional steady-state mathematical model was developed (figure 3). From the left side water flows under pressure p_e through the porous material. From the right side the surface is heated up to ϑ_i by a heat flux density, which is given by a constant surrounding temperature ϑ_0 according to a heat transfer coefficient α_0. Depending on the flow rate of the water and the heat flux density, the water attains the boiling temperature ϑ_S at the depth s_1 of the metal. The developing steam escapes from the system at the right side with a high velocity with the temperature ϑ_i. The pressure at the right side is 10^5 Pa, which is atmospheric. The thermal behaviour and the pressure distribution can be described by the following equations:

– heat balance

$$\frac{\alpha}{\dot m}(\vartheta_0-\vartheta_i) = c_D(\vartheta_i-\vartheta_S)+r+c_W(\vartheta_S-\vartheta_e); \quad (1)$$

– temperature distribution in the water region (region 1)

$$\vartheta(x) = \vartheta_S \exp\left(\dot m c_W \frac{x-s_1}{\lambda}\right); \quad (2)$$

– temperature distribution in the steam region (region 2)

$$\frac{\vartheta_i-\vartheta(x)}{\vartheta_i-\vartheta_S} = \frac{\exp\left(\dot m c_D \cdot \frac{s}{\lambda}\right) - \exp\left(\dot m c_D \cdot \frac{x}{\lambda}\right)}{\exp\left(\dot m c_D \cdot \frac{s}{\lambda}\right) - \exp\left(\dot m c_D \cdot \frac{s_1}{\lambda}\right)}; \quad (3)$$

– condition for the position of the boiling front s_1

$$-\lambda_1 \frac{d\vartheta}{{}_1dx_{s_1}} + \dot m r = -\lambda_2 \frac{d\vartheta}{{}_2dx_{s_1}}; \quad (4)$$

– heat transfer at the right-hand edge

$$\alpha(\vartheta_0-\vartheta_i) = -\lambda_2 \frac{d\vartheta}{{}_2dx_s}; \quad (5)$$

– pressure drop in region 1 [3]

$$\Delta p_1 = \frac{\dot m}{\varrho_W} s_1 \frac{\eta_W}{g} = \dot m s_1 C_1; \quad (6)$$

– pressure drop in region 2 [3] if $\Delta p_D < p_i$ and neglecting the capillary pressure in the boiling front

$$\Delta p_2 = \dot m(s-s_1)\left(\frac{\eta_D}{g}+\frac{\dot m}{h}\right)\frac{1}{\varrho_D} = \dot m(s-s_1)\,C_2. \quad (7)$$

The temperature and pressure fields in the porous medium are determined by these seven equations.

A closed analytical solution of the set of seven equations is not possible. The following data were derived iteratively.

The results for the case where the boiling occurs internally show that, with decreasing flow density rate $\dot m$, the surface temperature ϑ_i and the pressure drop

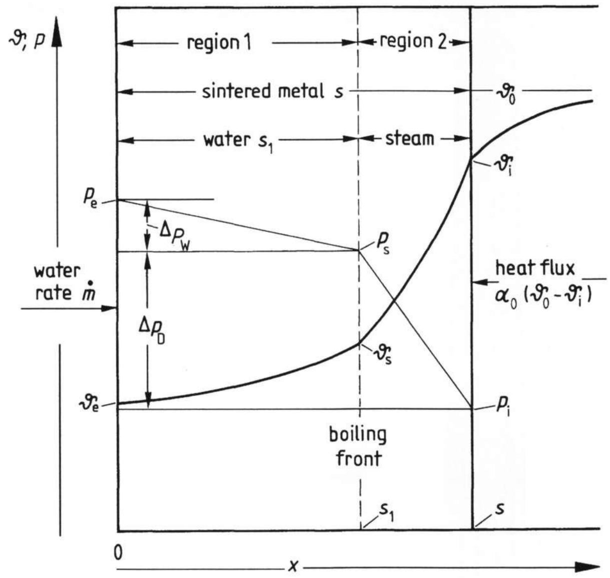


Figure 3. Pressure and temperature distribution in wet sintered material with an internal boiling front ($s-s_1$).

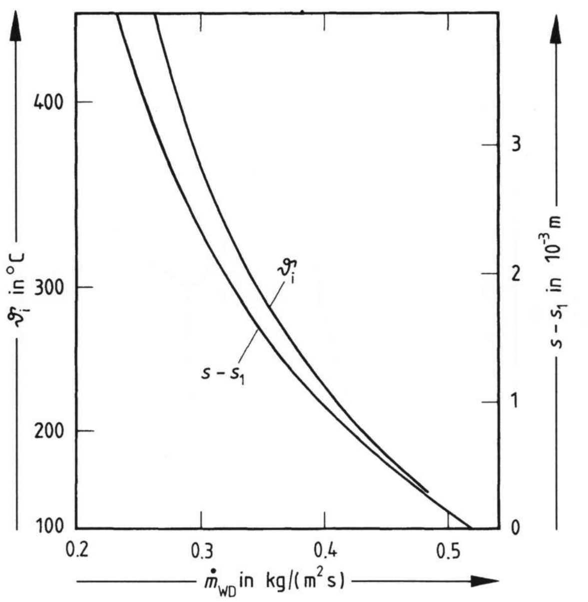


Figure 4. Surface temperature ϑ_i and steam layer thickness $s-s_1$ as a function of water flux density $\dot m_{WD}$. Thermal and material data see figure 5.

$\Delta p = \Delta p_1 + \Delta p_2$ increase (figures 4 and 5). The reason is that the boiling front s_1 migrates more and more into the material, and the pressure drop Δp_2 in the steam region is much higher than in the water region.

Without internal boiling the metal shows the reverse characteristic (figure 5). This is the reason that a system with both regions, one with an internal boiling front and one with an external boiling front shows flow instability when p_e and p_i are equal in both cases.

In a balanced system small changes in the heating conditions disturbs the unstable equilibrium. The worst case is the blocking of the water rate in the part with the steam layer. For a given water rate

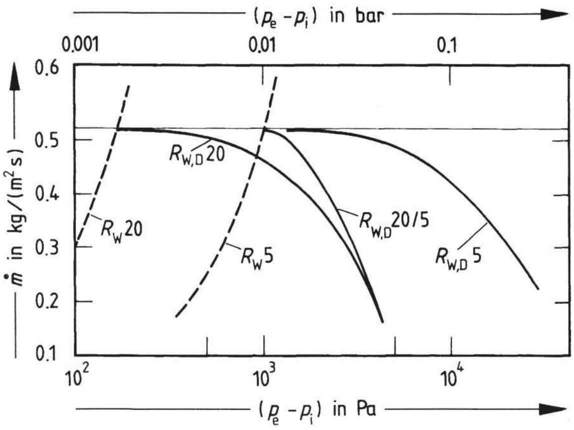


Figure 5. Pressure drop $\Delta p = \Delta p_W + \Delta p_D$ as a function of water flux density $\dot{m}_{WD}$. $\alpha = 1.25\,kJ/(m^2\,s\,K)$, $\lambda = 5 \cdot 10^{-3}\,kJ/(m\,s\,K)$, $c_D = 1.5\,kJ/(kg\,K)$, $r = 2250\,kJ/kg$, $c_W = 4.2\,kJ/(kg\,K)$, $\vartheta_0 = 1100\,°C$, $\vartheta_e = 90\,°C$. R5 material: $g = 1 \cdot 10^{-12}\,m^2$, $h = 0.5 \cdot 10^{-7}\,m$; R20 material: $g = 6 \cdot 10^{-12}\,m^2$, $h = 22 \cdot 10^{-7}\,m$. (Material code see table 1.) $\eta_D = 13 \cdot 10^{-6}\,Pa\,s$, $\varrho_D = 0.6\,kg/m^3$, $s = 5 \cdot 10^{-3}\,m$, $\vartheta_S = \Delta p_D/(4.3 \cdot 10^{-3}) + 100$, Δp_D in Pa; temperature range $100 < \vartheta_S < 110\,°C$.

$$\dot{M} \equiv F_W \cdot \dot{m}_W + F_{WD} \cdot \dot{m}_{WD} ,$$

the greatest possible pressure drop Δp_{max} in the system is given by the equation

$$\Delta p_{max} \equiv \frac{\dot{M}}{F_W} s\, C_1 \tag{8}$$

with $\frac{\dot{M}}{F_W} \equiv \dot{m}_{W_{max}}$.

The flow resistance Δp_{WD} is given by equations (6 and 7) with

$$\Delta p_{WD} \equiv \dot{m}_{WD} (s_1\, C_1 + (s - s_1)\, C_2) . \tag{9}$$

If it is reminded that the water rate density $\dot{m}_{WD}$ is correlated with $(s - s_1)$ (figure 4)

$$\dot{m}_{WD} = f(s - s_1)$$

and $\Delta p_{max} \equiv \Delta p_{WD}$ for a closed system, with equations (8 and 9) a critical steam layer $(s - s_1)_{crit}$

$$\dot{m}_{W,max} = \frac{s_1}{s} f(s - s_1)_{crit} \left(1 + \frac{(s - s_1)_{crit}}{s_1} \frac{C_2}{C_1}\right) \tag{10}$$

can be defined.

For $(s - s_1) < (s - s_1)_{crit}$ the water from behind is able to break through the steam layer and stabilize the system.

For $(s - s_1) > (s - s_1)_{crit}$ the water from behind is unable to break through the steam layer. The region with the inside boiling front is blocked, the whole water flows through the part with the external boiling front.

The pressure drop Δp_{max} can be controlled by a short high water rate $\dot{M}$ or by a high flow resistance of the wet porous material $(s \cdot C_1)$. The first can result in a great waste of water, the second can be influenced by the porosity of the material in the water region.

A plunger with two different layers of porosity, one with a high flow resistance (C_1) for the water region and one with a low flow resistance (C_2) in the steam region, must be advantageous for a steam plunger. Figure 5 shows the result of a calculation with an R5 material on the inside (high flow resistance, low porosity) and an R20 material (code of material cf. table 1) with lower flow resistance and higher porosity on the outside. The increase of pressure drop with decreasing flow rate density of water is much lower than for a homogeneous material. The tendency for instability is decreased but not eliminated.

5. Trials with a laminated plunger

The construction of different steam plungers is shown in figures 6a to c. The laminated plunger (figure 6b) was built on the basis of the knowledge discussed before. The inner layer was made from R5 material, the outer layer from 1 mm thick R20 material.

Trials with this plunger in a section of an IS machine showed a better water distribution. The plunger tip was wet under cold conditions. After glass contact the glass stuck after two or three cycles. Stable production was not possible. This was a disappointment. It was necessary to check the knowledge of the thermal behaviour of the steam plunger at the tip region.

The calculation of the mathematical model is based on stationary conditions. It is necessary to investigate also the time-dependent thermal factors. The surface temperature of the plunger changes strongly with the loading of the gob. The contact temperature ϑ_k between metal and glass can be calculated in the first instance by the equation

$$\vartheta_k = \frac{\vartheta_F \cdot b_F + \vartheta_G \cdot b_G}{b_F + b_G} \tag{11}$$

with $b = \sqrt{\lambda\, c\, \gamma}$.

Table 1 gives the calculated contact temperatures for the first cycles with different solid and sintered materials. R20 material shows a contact temperature of 280 and R5 material of 241 °C. After some further cycles without water penetration the contact temperature reaches the sticking temperature. The data in table 1 indicate that the plunger tip of R20 material runs noticeably hotter than a plunger tip of R5 material. The higher temperature results in a thicker steam layer and a higher flow resistance. The result of the trial indicates that with the first loading of the gob the critical thickness of the steam layer is exceeded. The water is with the second loading of the gob no longer able to penetrate the steam layer in the tip region. With every further cycle the tip temperature rises and reaches the sticking temperature.

Table 1. Thermal and permeation data for different sintered materials. $\vartheta_G = 1100\,°C$, $\vartheta_F = 100\,°C$, $b_G = 1000\ W\,s^{1/2}/(K\,m^2)$ [4]

material code	particle size in µm	porosity in %	heat penetration coefficient $b_M = \sqrt{\lambda c \gamma}$ (in $W\,s^{1/2}/(K\,m^2)$)		specific permeability		contact temperature in °C
			solid material	sintered material	g in $10^{-12}\,m^2$	h in $10^{-7}\,m$	
R20 Cr/Ni/Mo	20	≈30	7600	4560	6	22	280
R10 Cr/Ni/Mo	10	≈25	7600	5320	2	6	258
R5 Cr/Ni/Mo	5	≈20	7600	6080	1	0.5	241
R20 Cu/Sn bronze	20	–	14300	8580	10	20	204

To avoid sticking, the 1 mm thick R20 layer at the plunger tip was abraded (figure 6c). After this simple modification the plunger showed stable operation in the IS machine; there was no further glass sticking in the tip regions. The water distribution in the shaft and the finish region was good. The bottles produced had a good glass distribution, no cracks in the finish. The bursting pressure of the bottles was ≈10 % higher than for bottles which were produced under similar conditions with a solid air-cooled plunger.

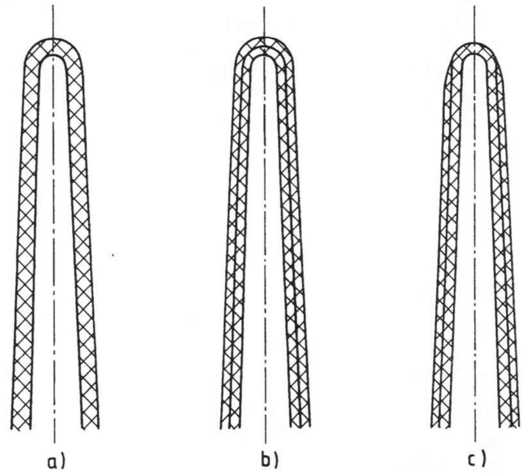
The trials showed that when operating with a steam plunger, the plunger tip is the vulnerable point. Porosity and heat penetration coefficient of the material must be carefully selected; the heat penetration coefficient must be high. Bronze could be a much better material than stainless steel (see table 1). An attempt to build a bronze plunger failed due to soldering problems. With more experience in handling the bronze material, it should be possible to overcome these difficulties.

One problem which could not be investigated is the permeability of the porous material over a longer time period. During the trials, which extended to more than 10 h operating time, no decrease of the permeability of the material was observed. After storage over some weeks obstructions were observed. The cause of these obstructions is not known.

6. Conclusions

The NNPB process for glass bottles can be operated with a steam plunger. The great differences in heat flux density over the surface of the plunger favour instabilities in the penetration of the water to the surface. The cause of these instabilities is the strong increase of the flow resistance due to internal boiling of the water. The high flow resistance, especially in the tip region, decreases the local water flow rate density and decreases the cooling effect.

The type of water feed is important. By introducing the water in discrete pulses there arises the possibility to induce pressure peaks, which are able to overcome the high flow resistance in regions where the boiling occurs internally. The disadvantage of this method is the waste of water in the regions where the boiling occurs externally.



Figures 6a to c. Construction of different steam plungers, a) sintered material with constant porosity, b) sintered material with low porosity on the inside and high porosity on the outside, c) like b) with abraded tip.

The thickness of the steam layer in the region where the boiling occurs internally is very important. For every type of plunger construction there exists a critical thickness for the steam layer. Exceeding this critical thickness results in local overheating and a reduction in the stability and effective cooling.

Regions which experience periodic high heat flux densities such as the tip of the plunger need a surface material of high heat penetration coefficient in order to avoid high temperature peaks during contact with the glass. For this reason bronze could be a better material for a steam plunger than stainless steel.

The permeability of porous plunger material used over a longer time must be intensely investigated. It was surprising that the loss of metal particles was very seldom observed.

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