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CFD MODELLING OF COOLING AIR IN THE NNPB PROCESS FOR GLASS CONTAINER PRODUCTION

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ABSTRACT
The aim of this paper is to scientifically understand the operation of the plunger cooling system and quantify the heat transferred from the parison to the plunger during the glass container production process. The paper highlights the results attained and the problems encountered during this investigation. The computational fluid dynamics (CFD) analysis of the cooling air flowing within the plunger cooling tube system used experimental data obtained from both the laboratory test rig and container manufacturing process on the shop floor. Preliminary results attained demonstrated choking together with recirculation of air in some areas along the airflow passage. This confirmed previous findings that areas of excessive tool temperature and rapid tool wear were caused by the ineffective heat extraction. The ineffective heat extraction can be attributed to the poor circulation of cooling air in the plunger. It was concluded that the cooling tube design should be reassessed to improve the airflow in the plunger cooling tube system.

INTRODUCTION
The production of glass containers up to the 1960's was by the blow and blow process. This process produced containers that exhibited poor quality finish, limited weight reduction and inconsistent mould cooling [1]. The development of the narrow neck press and blow (NNPB) process in the late 60's produced lightweight containers. These lightweight containers with its thin walls and smaller dimensional tolerances had a reduction in weight of 15%-30% [2]. The NNPB process is a two-stage process as shown in Figure 1. The gob drops into the blank mould and the plunger creates the parison. In the first stage he plunger presses and spreads the molten glass within the blank mould cavity. The parison cools when the metal plunger makes contact with the hot molten glass. However the parison maintains sufficient viscosity to retain its shape throughout the invert stage. The parison is inverted in the second stage. During the second stage the parison hangs and stretches under gravity. The blow head then covers the mould and blows the parison to its final shape.

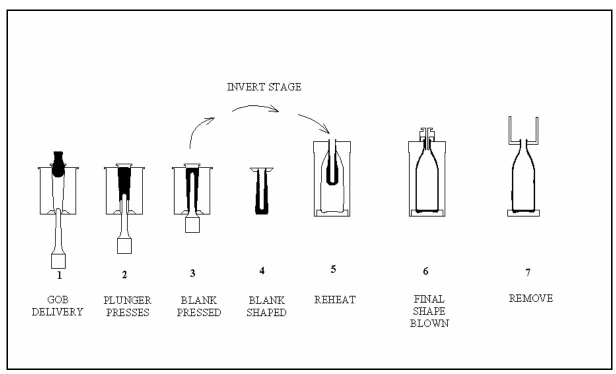

Figure 1. Narrow Neck Press and Blow Process

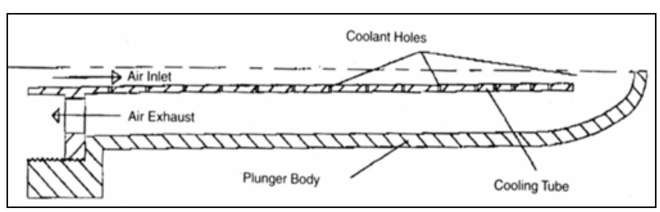

Figure 2. Cross section of an NNPB plunger

The most important component of the NNPB process is the plunger. The plunger has the dual function of forming the parison and distributing the glass within the container. Heat energy is extracted from the parison by the plunger, which uses air as the cooling medium. The air is distributed through a tapered steel cooling tube covered by an arrangement of radial holes within the plunger bore (Figure 2). Published work [2,3] showed that some plungers under normal working conditions were being subjected to extreme temperatures causing plunger material loss, reduced plunger coating material hardness and an increase in container contamination. The plunger should be subjected to a uniform temperature between 500°C-920°C [4] to prevent plunger material loss which causes container contamination. The plunger should extract sufficient heat without distorting the parison during the invert stage and affecting the plunger surface coating material.

There are many publications pertaining to the glass forming process [5,6] and its related temperatures [7-11] but very little on the fluid flow within the plunger cooling tube system. Initial work [2,12] carried out showed that the air flowing in the plunger cooling tube system was choking and recirculating within the cooling tube holes. This caused ineffective cooling in those areas. These affected areas corresponded with the plunger sections that were experiencing high temperatures and extreme wear [2]. The objectives of this paper are to examine the airflow within the plunger bore and the amount of heat extracted from the parison by the plunger cooling tube system.

NOMENCLATURE

V_{in}	Inlet velocity (m/s)
V	Airflow velocity
ν	Volumetric flow rate
A_i	Inlet Area
P_{in}	Inlet pressure (bar)
P_{out}	Outlet pressure (bar)
T_{inlet}	Inlet temperature (K)
T_{outlet}	Outlet temperature (K)
ΔT	Temperature difference
ρ	Density (kg/m^3)
C_p	Specific heat of air at constant pressure (J/kgK)
$\dot{m}$	Mass flow rate (kg/s)
Q	Heat absorbed (W)

EXPERIMENTAL METHOD

Laboratory Experiment

The laboratory experiment was devised to simulate the Indivudial Section (IS) machine glass container manufacturing conditions for the plunger cooling tube system. The purpose of this experiment was to ensure that the boundary conditions (P_{out}, V_{in}) used with the CFD model would be representative of the actual working system. The schematic layout of this experimental set-up is shown in Figure 3. An air compressor was installed at the start of the piping that carried the compressed air. An inlet control valve was installed at the end of this pipe. This pipe was connected with a control valve, airflow meter and pressure gauge linked with a reinforced PVC hose. This PVC hose was then installed to the inlet of the cooling tube. This connection was enclosed in the casing. The cooling tube was inserted into the plunger. An outlet was made on the casing and was installed with another reinforced PVC hose. A control valve and pressure gauge was connected to this hose. The pressure gauges and control valves were installed at both the inlet and outlet sections of the cooling tubes to maintain the current pressure difference (between 0.5 bar to 3 bar) used on the shop floor.

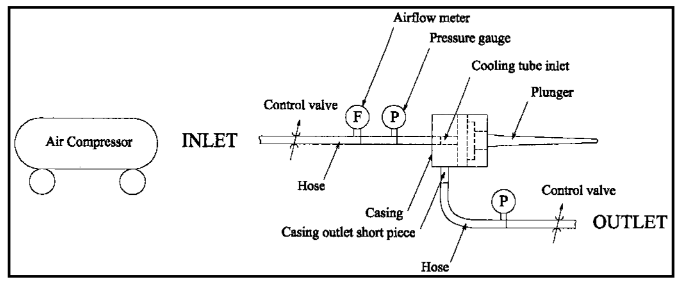

Figure 3.Diagram of the experimental layout

Experimental Procedure

The volumetric airflow into this system was measured to determine the inlet airflow velocity within the plunger cooling tube system. The volumetric airflow meter that was installed at the inlet of the plunger cooling tube system recorded this data. Tests were carried out to establish the volumetric airflow at a pressure difference ranging between 0.5 bar to 3 bar. This was the actual compressed air pressure range that was used on the shop floor. The results of the experimental set-up were recorded from 7 experiments at a specified range of exit pressures of 0 bar to 3 bar with intervals of 0.5 bar. Also the specified pressure difference between the inlet and outlet pressures were for a range of 0.5 bar to 3 bar. The pressure difference between the inlet and outlet pressure was obtained by controlling the control valve at the outlet section of the plunger/cooling tube system. A selected table of results is shown in Table 1.

P_{in} (bar)	P_{out} (bar)	ΔP (bar)	Volumetric airflow (dm^3/s)	Airflow velocity (m/s)
0.5	0	0.5	2.0	75.7
1.0	0.2	1.0	2.45	92.73
1.5	0.4	1.5	2.8	105.97
2.0	0.6	2.0	3.1	117.33
2.5	0.7	2.5	3.35	126.79
3.0	1.0	3.0	3.58	135.5

Table 1. Selected table of experimental results

The airflow velocity can be determined from Eq. (1)

$$V = \frac{\nu}{A_i} \quad (1)$$

The airflow velocity was calculated from the experimental data using the inlet diameter of the cooling tube (i.e. 5.8 x 10^{-3} m) obtained from the engineering drawings provided by the industrial collaborating company.

Shop floor Experiment

The thermal imaging analysis of the plunger and parison was carried out on the shop floor. The purpose of this exercise was to record the temperature distribution in the plunger and parison at the blank mould open stage immediately after the invert. This information was required to establish the temperature boundary conditions, representative of the actual working system. The temperature boundary condition was required in the CFD analysis.

Experimental Procedure

The thermal imager was calibrated by assessing the temperature of steam (100°C). The images of the temperature distribution along the plunger and parison were recorded approximately between 0.8 to 1 second after the blank mould opening stage. This was synchronised with the machine cycle times. These images were captured consecutively from the blank mould open stage to the parison invert stage at time intervals of 80 milliseconds between each frame. This helped to facilitate the selection of the plunger and parison at the precise moment immediately after the invert. This was important as it reduces the margin of error caused by the heat transfer from the plunger to the surroundings by conduction, convection and radiation.

The average temperature of the plunger recorded was 642.2°C at the blank mould open stage. This confirmed the previously reported result [13,14] confirming the NNPB operating temperatures were in a range of 500°C to 900°C. Following the thermal imaging experiment of the parison, it was shown that the average temperature along the external surface of the parison was 986.44°C. This confirmed the work carried out by others [13,14] indicating that the external parison surface temperature was approximately 1000°C.

CFD ANALYSIS AND HEAT EXTRACTION

The CFD analysis was carried out with a simplistic model having the assumption that the temperature of the parison internal surface was the same as the parison external surface. Hence it was also assumed that the parison internal surface temperature was the same as the external plunger surface temperature. Following this, the temperature boundary condition (i.e. uniform temperature T= 1000°C) was assumed along the length of the external plunger surface for the purpose of the CFD analysis. The CFD analysis also incorporated the boundary conditions (i.e. P_{out}, V_{in}), which were obtained from the laboratory experiment. The CFD analysis was repeated for each chosen set of boundary conditions. The inlet temperature (T_{inlet}), outlet temperature (T_{outlet}) and density (ρ) values of air flowing through the plunger cooling tube system were computated by the software during the CFD analysis. The mass flow rate ($\dot{m}$) of air flowing into the cooling tube system and the approximate amount of heat that was extracted/absorbed by the air were calculated incorporating the T_{inlet}, T_{outlet} and ρ values from the selected CFD analysis. The mass flow rate can be determined from Eq. (2)

$$\dot{m} = \left(\pi r^2\right) V_{in} \rho \quad (2)$$

The heat extracted/absorbed can be determined from Eq. (3)

$$Q = \dot{m} C_{p_{air}} \Delta T \quad (3)$$

RESULTS

The laboratory experiments highlighted that the casing enclosing the cooling tube inlet was not sufficiently airtight. This made attaining the required exit/out pressures difficult because there was a loss of pressure, which was due to the air escaping. A selected table of results for the CFD analysis is shown in Table 2.

V_{in} (m/s)	P_{out} (bar)	ρ (kg/m^3)	T_{inlet} (K)	T_{outlet} (K)	$\dot{m}$ (kg/s)	Q (W)
75.7	0	1.925	290	499.2	4.12 x 10^{-3}	865.4
86	0.12	3.034	289	469.5	7.955 x 10^{-3}	1441.5
92.73	0.2	2.903	288	466.8	8.13 x 10^{-3}	1458.7
105.97	0.4	2.52	288	466.1	7.551 x 10^{-3}	1352.4
117.33	0.6	3.488	286	450	0.012 x 10^{-3}	1905.3
126.79	0.7	4.392	285	436.6	0.016	2395.7
135.5	1	4.673	284	431.1	0.018	2644.1

Table 2. Tabulated results of the CFD analysis using a selection of boundary conditions.

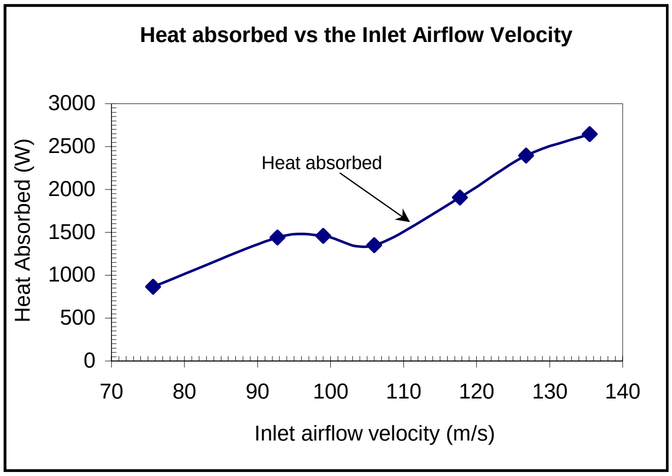

Figure 4: Heat Absorbed Against Inlet Airflow Velocity along the Plunger Cooling Tube System.

In Figure 4, the heat absorbed results for a selection of boundary conditions were plotted against the inlet airflow velocity. The results showed that the amount of heat absorbed from the plunger wall was proportional to the increase in the airflow velocity. However there was a dip in the heat absorption rate between the airflow velocities of 92.73 m/s to 105.97 m/s. This could be attributed to a single or a combination of factors such as recirculation of air, choking of the airflow or insufficient cooling tube holes, which was preventing the smooth extraction of heat from the parison.

CONCLUSION

The laboratory experiments have shown that the experimental set-up can be improved. The improvement in the experimental set-up (i.e. casing and connection joints should be secure to prevent loss of air and pressure) would assist in reducing the margin of error when recording the experimental data.

The CFD investigation showed that it would be advantageous to further examine the effectiveness of the plunger cooling tube system in the extraction and dispersion of heat energy from the parison. The effectiveness of the plunger cooling tube system can be improved by examining the cooling tube design (i.e. the arrangement and number of cooling tube holes). This improvement should eradicate/minimise the situation where the air flowing through the plunger cooling tube system experiences choking or recirculation. Following this the plunger surface should experience an even temperature distribution and effective heat extraction from the parison.

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