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Experimental model for casting problems

T.A. Kowalewski[1], A. Cybulski[1], T. Sobiecki[2]
[1]*IPPT PAN, Polish Academy of Sciences, Warsaw*
[2] *Warsaw University of Technology. Plock, Poland*

Abstract

The aim of our analysis is to provide a simple experimental model simulating the main flow characteristics accompanying casting processes. Hence, a hot liquid is provided under high pressure into an inclined box. The liquid propagates inside the box between two cold isothermal walls, passing obstacles simulating internal complexities of a mould. The main features of the experiment like flow acceleration and deceleration due to the obstacle, a free surface flow and sudden increase of the fluid viscosity as it cools down, are typical for a solidification of melt in a mould. As opposed to a real casting, this experimental configuration allows for full control of the experimental conditions and the full field measurements of the temperature and velocity fields. Collection of the quantitative transient data of the flow should permit the verification and validation of numerical models used for typical casting problems. The main aim of the investigations is to create an experimental benchmark for the mould-filling problem.

1 Introduction

Fluid flow and thermal effects during melting and solidification are of great interest in a number of manufacturing processes. Its main characteristic is a moving interface that separates two phases with different physical properties. In casting problems with a mould filling process a free liquid surface propagating in a complex geometry additionally complicates the flow pattern. Proper modelling of the flow becomes necessary for controlling fundamental parameters of the technological applications. However, due to the problem's complexity, the direct application of numerical methods to the engineering problem of solidification is not a trivial task. Errors appear due to the limited accuracy of different numerical methodologies and due to inevitable simplifications introduced in the models. The experimental verification of the models has gained special importance for phase change problems (Kowalewski & Rebow [1]). However, the available comparisons with real industrial casting processes is difficult and offers very limited number of parameters that can be accurately measured and compared with their numerical counterparts. Therefore, our present aim is to examine main characteristics of a typical casting problem for a simple case of small, transparent cavity filled under pressure with a hot liquid. These main characteristics are a rapid change of temperature due to the side-walls cooling and propagation of the free surface through a complex geometry. Phase change due to the cooling is simulated by strong increase of the fluid viscosity. Full field experimental data on temperature and velocity fields as well as particle tracking are used to collect transient data for the model. In the next step, these results will be compared with numerical simulations done with the casting code VULCAN [2].

2 Problem formulation

We consider forced convection in a rectangular, inclined box filled with viscous liquid. The cavity has square cross-section 38mm x 38mm and is 113mm high. The two side-walls are made from 7.5mm tick Plexiglas. The other two isothermal side-walls are made of copper. They are kept at low temperature Tc. Two Plexiglas plates located inside cavity are simulating shape complexity of a mould. They form three flow cavities connected only by 5mm high slits between the upper rim of the plates and the cold wall above (comp. Fig.1). The cavity inclination angle α varied from 12°- 45°. The hot fluid of initial temperature T_h is forced to the cavity through a 13mm circular opening made in the bottom wall. Both forced convection and residual natural convection within the cavity are responsible for the heat transfer through the cold side-walls.

Glycerol is used as the working fluid for it well known physical properties and very strong variation of viscosity with temperature. For the temperature range used (Tc=10°C, Th=50°C) the fluid viscosity changes its value almost twenty times dramatically altering a flow pattern at the cold walls.

The dimensionless characteristic parameters defining the problem are the Rayleigh and Prandtl numbers: $Ra=g\beta(T_h-T_c)L^3/\kappa\nu$, $Pr=\nu/\kappa$. In the above definitions g, L, κ, β, ν and ρ denote respectively the gravitational acceleration, cavity height, thermal diffusivity, coefficient of thermal expansion, kinematic viscosity and density of the liquid. To account for the inertial effects the Reynolds number $Re=DV/\nu$ is defined using characteristic flow velocity V at the inlet and the inlet diameter D.

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3 Experimental technique

Our main interest is directed to collecting quantitative information about the fluid free surface position as well as about velocity and temperature fields within a domain of a mid vertical plane of the cavity. For this purpose the flow images of the centre vertical cross-section have been collected periodically every 3s or 12s, approximately during fifteen minutes from the onset of flow. At each time step series of 3 to 10 RGB images were taken at short time interval. Later on they were used for the flow velocity evaluation (inter images cross-correlation) and for colour averaging procedures. Specially designed acquisition and image analysis software packages were used to obtain 2-D flow pattern (particle tracks) and temperature and velocity fields (Kowalewski at al. [3]).

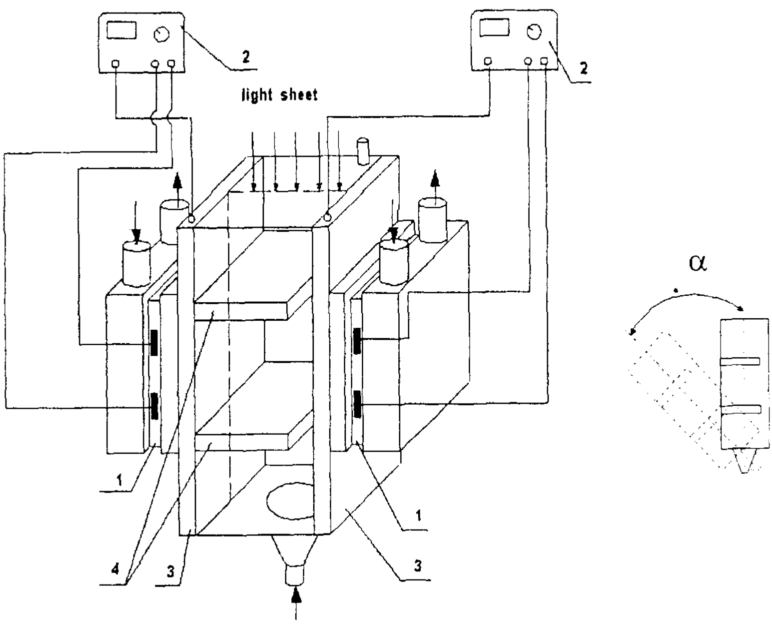

Figure 1: Schematic of the experimental system. 1 – Peltier elements, 2- controllers, 3- isothermal walls of the cavity, 4 – inner obstacles.

The experimental set-up (Fig. 1) consists of the rectangular cavity, a halogen tube lamp, the 3CCD colour camera and the 32-bit frame grabber (IC-PCI ITI). The flow field is illuminated with a 2mm thin sheet of white light from a specially constructed halogen lamp, and observed in the perpendicular direction. The 24-bit colour images of 768x564 pixels have been acquired using a 128MB Pentium III computer. This set-up permits us to gain in real time over 100 images before they have to be saved on the computer magnetic disk.

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The flow cavity has two isothermal walls made of a copper. Their constant temperature is maintained by two Peltier elements. The temperature of the liquid filling the cavity is maintained by immersing a metal container with the liquid in a water bath of a thermostat. The flow is initiated by pressurising air above liquid in the container.

The acquisition computer was used to control switching of the halogen lamp and to record readings from the thermostat and two thermocouples located at the inlet and at the top of the cavity. The first thermocouple indicated initial temperature of the fluid, whereas the second one signalised the end of the filling process. After the filling was finished an inlet valve was closed. From this moment a residual natural convection accompanied by cooling of the liquid trapped in the cavity was studied.

Thermochromic Liquid Crystal (TLC) tracers have been applied to measure both temperature and velocity flow fields. The TLC based temperature visualisation is based on the property of some cholesteric and chiral-nematic liquid crystal materials to reflect definite colours at specific temperatures and viewing angle. The colour change for the TLC ranges from clear at ambient temperature, through red as temperature increases and then to yellow, green, blue, and finally clear again at the highest temperature. The response time of TLCs equals about 10ms. It is short enough for typical thermal problems in fluids. The mean diameter of the unencapsulated TLC tracers used in the experiments is about 50μm. The temperature measurements are based on a digital colour analysis of *RGB* images of the TLCs seeded flow field. For evaluating the temperature the *HSI* representation of the *RGB* colour space is used [3]. The incoming *RGB* signals are transformed pixel by pixel into *Hue, Saturation and Intensity*. Temperature is determined by relating the hue to a temperature calibration function. Our 8-bit representation of the hue value assures resolution better than 1%. However, the colour - temperature relationship is strongly non-linear (comp. [3]). Hence, the accuracy of the measured temperature depends on the colour (hue) value, and varies from 3% to 10% of the full colour play range. The most sensitive region is the colour transition from red to green and takes place for a temperature variation less then one Celsius degree.

The 2-D velocity vector distribution has been measured by digital particle image velocimetry (DPIV). By this method, the motion of the scattering particles, observed in the plane of the illuminating light sheet, are analysed. For this purpose, the colour images of TLC tracers are transformed to B&W intensity images. After applying special filtering techniques bright images of the tracers, well suited for DPIV, are obtained.

The magnitude and direction of the velocity vectors are determined using a FFT-based cross-correlation analysis between small sections (interrogation windows) of one pair of images taken at the given time interval. The average particle displacement during a given time interval determines the velocity vector representing the section investigated. To improve the accuracy and dynamics of the velocity measurements short sequences of images have been taken at every time step. The cross-correlation analysis performed between different images of the sequence (time interval between pairs changes), allows us to preserve similar accuracy for both the low and high velocity flow regions. The resolution of the velocity field evaluation was improved using the recently developed ODP-PIV method (Quénot et al. [4]) of image analysis. Typically accuracy of 0.15 pixels is possible for the ODP-PIV method. It means that for typical displacement vector of 10 pixels the relative accuracy of the velocity measurement (for single point) is better than 6%.

To get a general view of the flow pattern, several images recorded periodically within a given time interval have been added in the computer memory. Displayed images are similar to the multiexposed photographs, showing the flow direction and its structure.

The flow images are used to evaluate shape and location of the fluid front moving across the cavity. These measurements are performed manually using image analysis software. The accuracy of a single point measurement is about 1 pixel, what corresponds to 0.07 mm.

4 Results

The experiments have been performed for 99% glycerol initially heated to 50°C. The hot fluid was introduced to the at first empty cavity through the bottom opening. The cold walls of the cavity were kept at the temperature 10°C. In this range of temperature the viscosity of glycerol changes from $160 \cdot 10^{-6} m^2/s$ (45°C) to $2950 \cdot 10^{-6} m^2/s$ (10°C). The cooling of liquid by heat transfer to the cold walls coupled with the forced and natural convection in the cavity are studied.

To investigate effects of the gravity on the filling process the cavity was inclined (comp. Fig.1). By increasing the inclination a role of natural convection decreases. It is because effectively the vertical elevation of the cavity decreases. Three angles of inclination were used 13.5°, 26° and 45°. During the filling process the inclination angle effects mainly the flow interaction with the two internal obstacles. Due to the inclination fluid "falls down" through the gap after the first and the second cavity is filled. For the higher inclination angle typical effects characteristic for the "dam breaking problem" can be recognised. After the fluid breaks-up trough the gap a well visible surface wave propagating against the flow was observed. It takes about 1min until the surface smoothes out and the regular propagation of the flat interface recovers.

The second parameter varied in the experiments was the filling flow rate. By changing pressure in the container storing the preheated glycerol the flow rate through the inlet was set. Three different flow rates were applied: $5.5 cm^3/s$, $2.5 cm^3/s$ and $0.6 cm^3/s$. It corresponds to Reynolds number for the inlet varying from 2.5 to 0.2. The Reynolds number variation effects mainly the cooling rate.

At lower flow rates residual natural convection starts to intensify cooling of the fluid after each section of the cavity was filled. The characteristic recirculating flow pattern develops in the first section already after the fluid interface passes the division between sections.

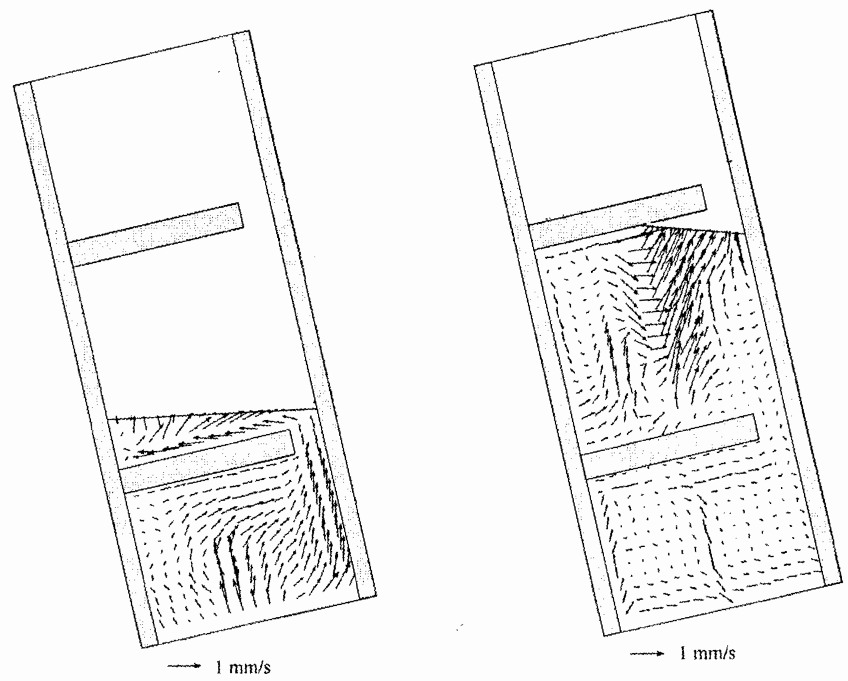

Figure 2: PIV evaluated velocity fields for cavity inclined at 13.5°; fluid passing the first (left) and the second obstacle (right).

The Rayleigh and the Prandtl numbers calculated for the experimental parameters are $6.5 \cdot 10^6$ and 3720, respectively. The non-dimensional numbers are calculated for the mean liquid temperature (30°C). Despite relatively high value of the Rayleigh number the natural convection plays only a secondary role, mainly during the cooling process after the inflow is stopped. In fact, our configuration lacks presence of the hot wall and the traditional definition of the Rayleigh number, based on the maximum of temperature differences, gives overestimated value.

Over 30 different experimental runs have been performed. They cover different flow regimes, both the fast initial transients and the final quasi-steady cooling of the fluid. Each run consists of 50-100 pairs of images taken at constant time steps during the filling process (2-5min) and about 50-70 pairs of images taken during 15min after the inflow was stopped. A large number of experimental data was collected. In the following we have decided to select only a small sample of the results. The detailed collection of a data can be found in Sobiecki [4].

Figure 2 shows examples of the flow structure observed for the cavity inclination angle 13.5°. At this angle the observed filling process characterises almost horizontal interface propagating with a constant speed across the cavity. Only during penetration of the fluid through the first and the second gap a short disturbance of the interface shape was observed. The strong cooling of the fluid by the side walls dramatically increases its viscosity, apparently retarding the flow in the regions close to the walls.

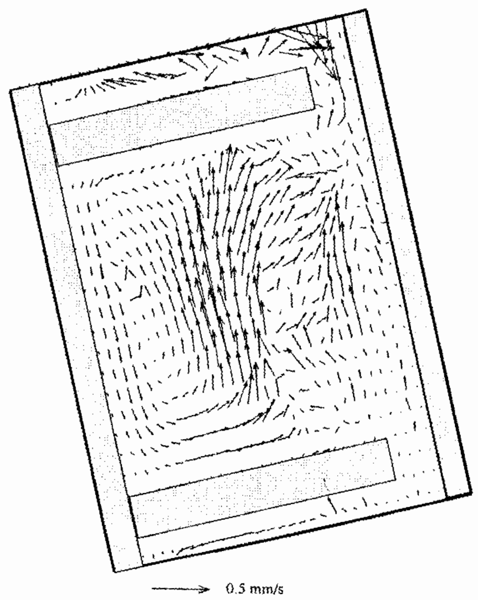

Figure 3: PIV evaluated velocity field in the middle section of the cavity.

Figure 3 shows blow-up of the flow pattern in the second section during the filling process. One may recognise the main flow stream deflected from the upper wall due to the increased viscosity. The fluid "prefers" to flow through less viscous centre of the cavity. This flow induces secondary circulation transporting cold liquid from the lower wall and increasing the heat transfer and the overall cooling rate. After closing the inlet valve fluid trapped in the cavity starts to cool down. This rapidly increases the fluid viscosity. The natural convection develops in the cavity with two, almost symmetrical, counter-rotating circulations. A very similar pattern is observed for the intermediate inclination (26°). However, a decreased role of the natural convection leads to formation of so called "hot spots". These are small regions where of the hot fluid is trapped and its cooling is sustained mainly due to the heat conductivity. Figure 4 shows the temperature

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distribution in the cavity visualized by colour response of the liquid crystal tracers. Formation of the "hot spot" in the left part of the middle cavity is well visible. In such spots the observed flow is mainly due to the volumetric shrinkage of the fluid. Such regions can be well identified in the velocity field due to the focussing topology of the flow pattern. To some extend the "hot spots" reassemble void cavities left in the solidifying material, if the cooling process is non-uniform. Such cavities are the major problems for industrial casting, seriously degrading mechanical properties of the product.

Figure 4: TLC temperature visualization (left) and evaluated isotherms (right) observed just after closing the inlet; inclination of the cavity 26°. Blue colour (dark regions) indicates higher temperature.

Figure 5 demonstrates similar phenomena observed for the highest investigated inclination angle (45°). It is clear that after filling the cavity the temperature distribution becomes instantaneously non-uniform. Close to the cold walls fluid cools down rapidly changing its viscosity. This reduces local convective heat transfer, leaving in the central part of the cavity the hot regions with only residual flow surrounding them. The cooling process by the thermal conductivity is not effective, especially for fluids characterised by high Prandtl number. Hence, local hot spots develop in regions where cooling retards. These are regions where the possibility of non-uniform shrinkage of the solidifying material increases.

Obviously, the experimental data collected for the cavity are far from the real casting problem. However, we believe that the main features of the

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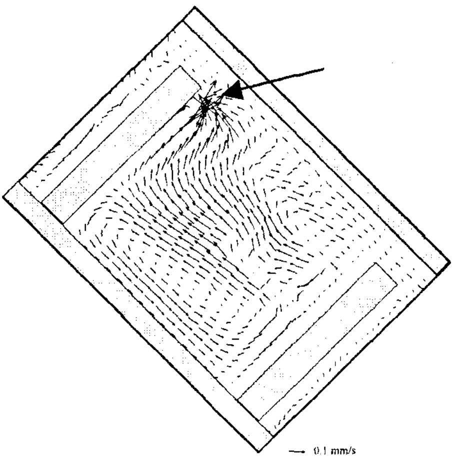
experiment like free surface flow, its acceleration and deceleration on the obstacle, and sudden increase of the fluid viscosity at the side walls are typical for a solidification of melt in a mould. Opposite to a real casting our experimental configuration allows to identify flow structures and gives full field quantitative information on velocity and temperature fields at selected time steps. It should permit to verify and validate numerical models used for typical casting problems in their parts responsible for the heat and mass transfer.



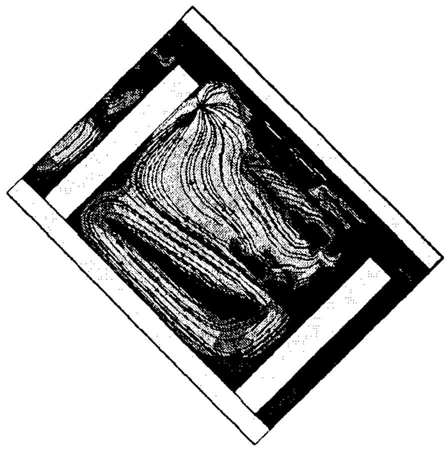


Figure 5: PIV evaluated velocity field (left) and streamlines integrated for this field with colour coding of velocity value (right) ; middle section of the cavity observed 180s after closing the inlet; shrinkage of liquid at the "hot spot"; inclination of the cavity 45°.

Our present attempt is to describe main features of the observed flow using a typical casting code VULCAN [2]. This code solves the Navier-Stokes equations using a stabilised finite element method. The basic ingredients of the numerical solutions make use of a finite increment calculus formulation, a semi-implicit fractional step technique for time integration and a standard Galerkin method for space discretization using linear tetrahedra for interpolating the velocity and pressure variables. It allows for a relatively flexible description of our complex geometry and to perform calculation for a free, deformable fluid surface. Full 3D calculations are performed to obtain results that simulate as close as possible their experimental counterparts. By implementing thermal properties of the walls and variable (temperature dependent) fluid properties, preliminary calculations are performed to simulate the filling of the first section of the cavity. Details will be given in a separate publication.

5 Concluding remarks

The experimental model of the mould filling process was investigated. The experimental data were collected to create a reference database for comparison with numerical results. The method of simultaneous measurement of the flow and temperature fields using liquid crystal tracers has been successfully applied to collect transient information on the flow. The collection of results illustrates the complexity of the flow. The heat flux to the side cold walls is responsible for creation of the tick, viscous layer, retarding the main flow. It diminishes convective heat flux from the inner regions of the cavity. The cooling at some spots of fluid trapped in recirculation zones is delayed, leaving the "hot spots". In these places a slow conductive cooling and volumetric shrinkage of fluid can generate void bubbles, a common plague of any industrial casting. The observed interactions of free surface flow with the obstacles create an additional challenging problem for numerical simulations.

Acknowledgement

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