Experimental benchmark for casting problems

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Abstract
The problem motivating the current work is a mould filling during casting process. The aim of our analysis is to provide a simple experimental model simulating the main flow characteristics accompanying such process. Hence, the hot fluid is supplied under high pressure into an inclined box. Fluid flows inside the box between two cold isothermal walls, passing obstacles simulating internal complexity of a mould. The main features of a casting process, like a free surface flow and increase of the fluid viscosity followed by solidification, are investigated in the model. Opposite 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 allow for verification and validation of the numerical models used for typical casting problems. Our main aim is to create an experimental benchmark for the mould-filling problem.

1. Introduction
Heat transfer between two media involving liquid-solid phase transition is important in both nature and industry. There is general agreement that proper understanding of flow characteristics is usually crucial for predicting and modelling phase transition processes. Progress in numerical techniques allows for the simulation and modelling of phase change problems in complex flow configurations. Nevertheless, due to the problem complexity, application of numerical methods to many engineering problems is not a trivial task. Errors appear due to limited accuracy of different numerical methodologies and due to inevitable simplifications introduced in the models. Hence, the experimental verification of the models has gained special importance. However, a direct comparison with a real industrial casting process is difficult. Only very limited number of parameters can be accurately measured and compared with their numerical counterparts. Therefore, our present aim is to examine the main characteristics of a typical casting problem for a simple case of a 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 motion of the free surface through a complex geometry. Effects of phase change due to the cooling and strong increase of a melt viscosity are of our particular interest. Full field experimental data on temperature and velocity fields as well as particle tracking are used to collect transient data for the model. These data are compared with numerical simulations done with the popular fluid mechanical code Fluent (Fluent Inc.). In the next step our plan is to test reliability of typical casting codes (Vulcan, Procast) by applying them to our simple model.

In the experiment temperature and velocity fields of the flow are monitored using thermochromic liquid crystals (TLCs). Small particles of the liquid crystal material suspended in liquid ideally play the role of tracers following the flow pattern. Using the standard Particle Image Velocimetry (PIV) technique, the local velocity of the flow is measured by cross-correlating two sequential images. In addition these particles change colour with their temperature (Hiller and Kowalewski, 1986). Hence, after proper calibration, they behave as small thermometers simultaneously monitoring local fluid temperature. The application of high resolution colour camera and digital image analysis gave impulse to develop the feasible concept of digital particle image thermometry. The possibility to combine PIV and Particle Image Thermometry (PIT) was demonstrated by Hiller et al. (1993), and its applicability to the phase change studies was shown recently (Kowalewski et. al. 1998). The aim of the present experiments is to generate full field data of temperature and velocity, which can be directly compared with their numerical counterparts. We believe, that despite the limited accuracy of the measurements, the non-intrusive character of the method and the possibility of instantaneous and full field measurements of velocity and temperature, create a valuable tool for quantifying thermally driven flows.

1. Problem description

The experiments are performed in a small (113mm x 38mm x 38mm) rectangular cavity made of 7.5mm Plexiglas. The two opposite side walls made of copper are assumed to be isothermal. They are kept at low temperature T_c. Two Plexiglas plates located inside the cavity are used to simulate the complexity of the shape of a mould. They form three flow partitions connected only by 5mm high slits between the upper rim of the plates and the cold wall above (comp. Fig.1a). The inclination of the cavity angle α varied from 8^o- 45^o. The hot fluid of initial temperature T_h is forced to the cavity through a 13mm circular opening made in the bottom wall. Both, the forced convection and the residual natural convection within the cavity are responsible for the heat transfer through the cold side walls. Some more details concerning the experimental setup can be found in Sobiecki (1999) and Kowalewski et al (2001).

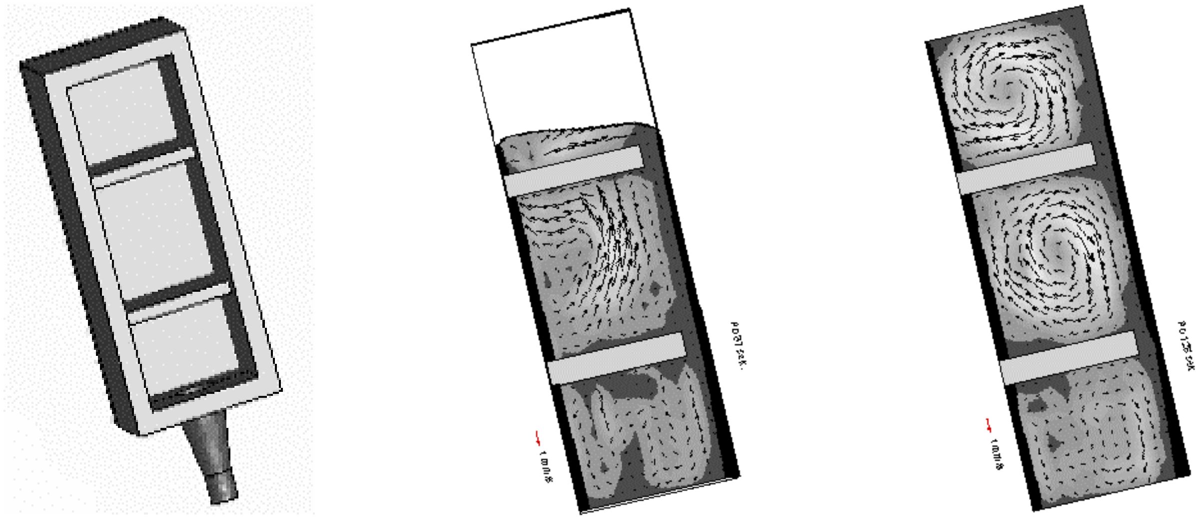

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Figure 1. Geometry of the cavity - (a); water filling cavity and freezing at the side walls:
PIV evaluated velocity field with contours of the velocity magnitude and the ice layer (black strips) observed after 82s - (b) and 128s - (c); inclination $\alpha=8^o$, T_c=-15°C, T_h=3°C, Q=$1.1 \cdot 10^{-6} m^3/s$.

As working fluids, water and glycerol are used. Water is used for its low viscosity to simulate high Reynolds number free surface flow interacting with the mould as well as the phase change (freezing) effects. The temperature range applied in the freezing experiments was $T_{c=}$ -15°C for the cold isothermals walls, and T_h=3°C as an initial fluid temperature. In practical situations, like solidification of metals, viscosity of the melt rapidly increases close to the phase change point. To investigate effects of the variable viscosity, glycerol is used as the working fluid in our model experiment. It was selected for its well-known physical properties and its strong variation of viscosity with temperature. For the temperature range used in the experiments with glycerol ($T_{c=}$10°C, T_h=50°C), its viscosity changes almost twenty times dramatically altering the flow pattern at the cold walls.

The temperature of isothermal walls and the initial fluid temperature are maintained at a constant value by two thermostats. The experiment starts by opening abruptly the inlet valves at the bottom wall for the pressurised preheated fluid. By changing pressure in the container the flow rate through the inlet was set. It varied from $0.6 \cdot 10^{-6} m^3/s$ to $5.5 \cdot 10^{-6} m^3/s$ for glycerol and up to $18 \cdot 10^{-6} m^3/s$ for water as the working fluid.

The experimental set-up used to acquire temperature and velocity fields consists of a 3CCD colour camera and a 32-bit PCI bus frame grabber. The 24-bit colour images of 768x256 pixels are acquired using a Pentium III computer. The flow field is illuminated with a 2mm thin sheet of white light from the halogen lamp, and observed in the perpendicular direction. Both velocity and temperature fields are monitored using unencapsulated Thermochromic Liquid Crystal (TLC) tracers. Digital evaluation of colour of the tracer images collected for the selected flow cross-section (Digital Particle Image Velocimetry and Thermometry) is used for simultaneous and fully automatic measurements of temperature and velocity 2-D flow fields.

The dimensionless 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, $Re=Q/D\nu$, is defined using the imposed flow rate Q and the cavity width D. In the experiments with water as a working fluid Ra varied from 10^7 - 10^8, $Pr = 8$, $Re = 100 – 500$. For glycerol as a working fluid Ra varied from $10^6 – 10^7$, $Pr = 6300$, $Re = 0.05 – 2$. It is clear that these numbers are far from the values observed in real industrial situations. Nevertheless, the flow appears to demonstrate several common characteristics. Our main interest is directed to the collection of quantitative information about the velocity and temperature fields, and the fluid interface position, for the centre vertical plane of the cavity. It is worth noting the relatively strong deformation of the interface during the filling process. In addition, the solidification front appearing at the both side walls efficiently modifies the flow structure. These strongly dynamic effects create a challenging problem for the numerical simulations.
A numerical simulation of the problem was performed using a finite difference code Fluent, with a laminar viscous flow model and VOF method for free surface flow simulation. For water as a working fluid, the main physical properties: viscosity, thermal conductivity, and specific heat were assumed to be constant. An anomalous thermal variation of the water density implemented in the numerical code is described by the fourth order polynomial, given elsewhere (Kowalewski and Rebow 1999). For glycerol as a working fluid, the temperature independent properties are thermal expansion coefficient, thermal conductivity, and specific heat. The density is linear function of temperature and the viscosity variation is described by the empirically estimated polynomial function given by Sobiecki (2000). The Plexiglas walls are assumed to be adiabatic and the fluid temperature at the inlet to be constant. Due to constraints of the available version of the code, the thermal effects were implemented after the isothermal VOF solution was achieved. Hence, only qualitative comparison is possible at the present stage.

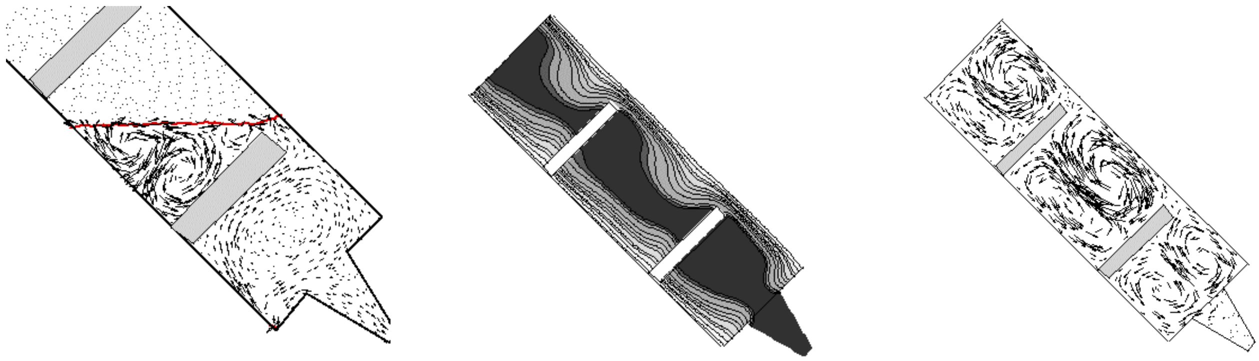

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Figure 2. Numerical simulations (Fluent), inclination α=45°: water filling second partition of the cavity, development of recirculation zones –(a); cooling process for the cavity filled with glycerol T_c=10°C, T_h=30°C: temperature - (b) and velocity - (c) fields.

2. Selected results

A large number of experimental data were collected. The detailed description of the data will be given in the forthcoming thesis (Cybulski 2002). In the following, we show only a small sample of the results illustrating the methodology of our investigation. We discuss three main flow features: dynamic effects accompanying the free surface flow, the melt cooling process, and the solidification.

2.1 Free surface flow

The free surface flow experiments are aimed at studying interaction of fluid filling the cavity with the inside geometry and the possible effects of such interaction on the established flow pattern and overall heat transfer.

To investigate effects of the gravity on the filling process, the cavity was inclined. By increasing the inclination the role of natural convection decreases, whereas flow interactions with the internal divisions becomes more evident. Three angles of inclination were used: 13.5^o (11.4^o in some cases), 26^o, and 45^o. During the filling process the inclination angle mainly affects the flow interaction with the two internal obstacles. Due to the inclination, fluid film slips 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 through the gap an easily visible surface wave, propagating against the flow, is observed. It takes about 1min until the surface smoothes out and the regular propagation of the flat interface recovers. In the case of water as working fluid, the effects of fluid inertia evidently deform the surface, exciting the standing wave. The second parameter varied in the experiments was the filling flow rate. The flow rate variation affects mainly the cooling rate of the fluid. At higher flow rates, intense recirculation develops immediately after some part of the cavity is filled. Fluid falling down from the inlet along the bottom wall fills the lower part of the cavity and cools down at the lower isothermal wall. This generates the main clockwise recirculating zone, which fills almost the whole part of the first chamber. After about 80% of the first partition is filled the secondary, counter-rotating recirculation zone develops, intensifying heat transfer from the upper isothermal wall. After the partition is filled the recirculation becomes slower in this region. It seems that the free surface flow is mainly responsible for generating strong flow agitation. The second strong flow disturbance is generated after fluid passes the gap between partitions. Sudden ejection of the fluid through this opening and its penetration down along the partition wall triggers again the recirculation flow, similar to the main vortex observed for the first partition, but rotating in the reverse direction. Due to this recirculation, the flow is well mixed and the temperature distribution at the lower parts of the partitions is quite uniform. When the second partitions fills up, the secondary, smaller recirculation develops along the upper wall. It mainly consists of hot fluid, which is soon ejected through the gap opening to the last partition. There is only a little amount of fresh, hot fluid transported to the lower recirculation zone. Fluid trapped there, cools down relatively fast. But mixing is rather poor in the lower regions, particularly for high Prandtl number fluid (glycerol). In the recirculating regions, so called "hot spots" are usually observed, i.e. dead flow zones where fluid cooling is mostly by conduction. After the whole cavity is filled the flow is immediately interrupted. Shortly after, large clockwise recirculation zones fill all three partitions (comp. Fig. 1c).

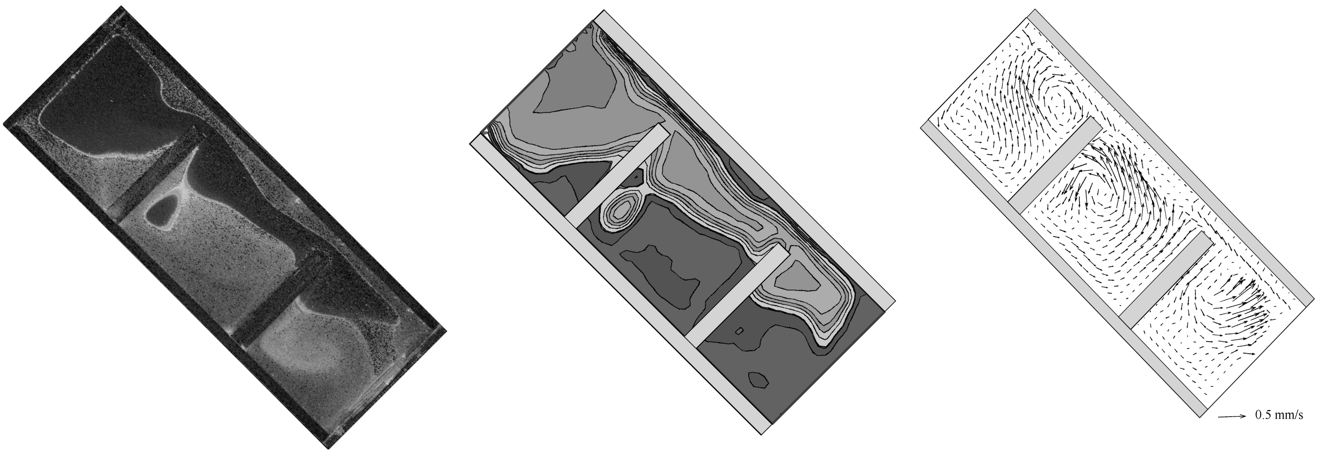

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Figure 3. Cooling process observed for cavity filled with glycerol shortly after flow stops; α=45^o, T_c=10°C, T_h=45°C. (a) – TLC tracers, blue (dark) indicates higher temperature regions; (b)- PIT evaluated isotherms; (c) – PIV evaluated velocity field;.

Due to the temperature gradients in the fluid, natural convection starts to develop. However, even at the lowest investigated flow rate, the role of residual natural convection in overall heat transfer seems to be negligible, as long as the force convection is sustained. The convective mixing appears to be very effective for the low Prandtl number fluid, namely water. As soon as the flow stops, natural convection becomes a driving mechanism regulating further cooling and eventual phase transition. The characteristic double vortex with recirculating flow pattern develops in the each partition of the cavity with downwards flow along the isothermal walls and return flow in the centre. Little or no flow is present through the connecting gaps. Due to the asymmetry of the partitions geometry and inclination of the cavity, the upper vortex is usually less developed.

2.2 Cooling process

After closing the inlet valve, fluid trapped in the cavity starts to cool down. Thermal conductivity of fluid supported by natural convection attempts to homogenise temperature distribution within the cavity. For low Prandtl number fluids, like metals, the thermal conductivity plays a dominating role. Nevertheless, natural convection in this case also triggers non-uniformity of the temperature (and concentration for alloys). In our experiments, for water, a fluid of the relatively low Prandtl number, temperature distribution in the cavity still remains non-uniform after a relatively long time. Stable thermal stratification develops along the isothermal walls, and cooling is mainly due to the conduction. Residual natural convection is very weak, especially close to the freezing point. One of the possible reasons is the anomaly in the variation of the water density with temperature. Close to the freezing point, namely at 4^{o}C, fluid buoyancy changes its sign and the cold fluid becomes lighter, compensating for any convective motions.

In the experiments with glycerol the temperature distribution in the cavity is strongly non-uniform after closing the inlet. Mixing of fluid during the filling process is relatively weak, in this case, and characteristic "snake like" region of hot fluid reproduces the trace of the main flow stream (comp. Fig. 3a). It is mainly due to the strong variation of the fluid viscosity with temperature. The highly viscous cold fluid becomes trapped and there is little mixing between cold and hot zones. After a short period the natural convection develops in the cavity, with two counter-rotating circulations. A very similar pattern is observed for the whole range of investigated inclinations (12^{o} - 45^{o}). Decreased heat transfer in the centre of the recirculating zones usually leads to the formation of so called "hot spots". These are small regions where the hot fluid is trapped, and its cooling is sustained mainly due to the heat conductivity. Figure 3b shows the temperature 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 easily visible. To some extent the "hot spots" resemble void zones left in the solidifying material, if the cooling process is non-uniform. Such zones are the major problem for industrial casting, seriously degrading the mechanical properties of the product. In these regions, flow is mainly due to the volumetric shrinkage of the fluid. This can be well identified in the velocity field, due to the focussing topology of the flow pattern.

Numerical simulation for this process seems to show only qualitative agreement (Fig. 2b,c). The hot zone, easily visible for the last partition in the experiment, is absent. The flow pattern is only partly similar. The very probable reason for these discrepancies is our method of generating solutions by separating it into two steps: free surface flow of isothermal fluid and cooling of the cavity filled with fluid.

2.3 Solidification

The solidification process is studied for the inclined cavity filled with water, both for the case of the void cavity and the cavity with the above-mentioned divisions. The void cavity is selected for easy analysis of the freezing front propagation. In this case growth of an almost uniform layer of ice at the cold isothermal walls is observed.

The measured and calculated flow velocities are very small. Apparently, the residual convective motion has little effect on the phase change process. Initially the growth rate of ice at the lower wall is faster than at the upper one (comp. Fig. 4). But after about 4 minutes this difference vanishes completely and the uniform growth of the ice layer is observed for both walls.

This relatively simple solidification process appeared to be difficult to resolve numerically. It was found that the thermostated metal walls did not maintain their initial temperature (-15°C), and corrected values measured during the experiment had to be used instead. Qualitatively numerical counterparts show very similar uniform growth of the ice layers. However, the simulated initial growth rate at the upper wall is much higher. Whereas, in the experiment it is necessary to wait over 3 minutes for a 2 mm layer of ice, the numerical code predicts only 1 min growth time. This discrepancy is probably due to a delayed contact of the fluid with the upper wall during filling process. To improve the modelling, additional investigations will be undertaken to take into account heat transfer during the cavity filling time, and to solve the conjugate heat transfer problem including the both cooling walls.

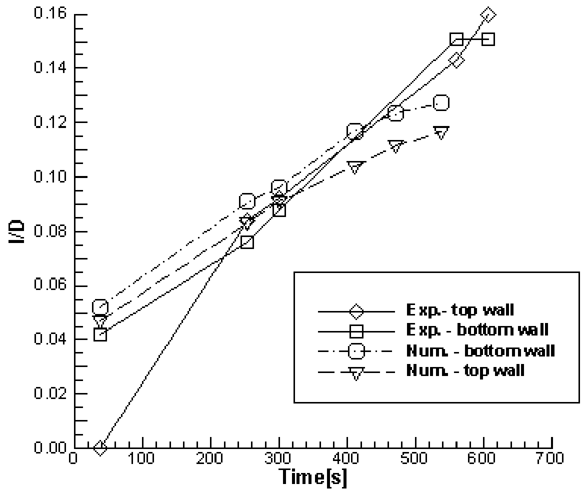

Figure 4. Non-dimensional thickness of ice layer growing in the void cavity filled with water: inclination angle $\alpha=11.4^o$, lower wall temperature T_{cl}=-7°C, upper wall temperature T_{cu}=-6°C, initial fluid temperature T_h=3°C. Solid lines – experimental data for the upper and lower walls, dashed lines - numerical prediction.

Conclusions

The simple model of the mould was used to study a free surface flow and solidification. It allowed for the collection of quantitative data on the flow pattern, the velocity and temperature fields, and the interface shape. Preliminary numerical study of the experimental cases shows only qualitative agreement. Several details differ, like formation of the recirculating zones, and the growth rate of the solid phase, sometimes quite seriously. It appears that numerical modelling needs additional improvements. Its verification appears possible with the help of the available experimental data.

Obviously, the experimental data collected for the cavity are far from the real casting problem. However, the main features of the 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. Hence, we hope that the experiment can be used to verify and validate numerical models used for typical casting problems, at least those parts responsible for the heat and mass transfer.

Acknowledgement

This work was supported by Polish Scientific Committee (KBN Grant No. 8T09A00820). Parts of the computations were performed at the computer centre of the Warsaw University of Technology (COI).

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