NUMERICAL ANALYSIS OF MOULD FILLING AND GATING DESIGN FOR ALUMINIUM MOULD CASTINGS

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ABSTRACT

A fuzzy logic based optimization is applied to obtain an optimal design of a typical gating system used for the gravity process to produce aluminum parts. This represents a novel application of coupling fuzzy logic techniques with a foundry process simulator, and it is motivated by the fact that a scientifically guided search for better designs based on techniques that take into account the mathematical structure of the problem is preferred to commonly found trial-and-error approaches. The simulator applies the finite volume method and the VOF algorithm for CFD analysis. The technique was used to solve 3D gating system design problems using two design variables. The results clearly show the effectiveness of the proposed approach for finding high quality castings when compared with current industry practices.

INTRODUCTION

Gravity die casting (GDC) processes are capable ofmaking complicated high integrity components,such as wheels, cylinder heads, engine blocks and brake callipers, at lower cost than most other casting methods. Cycle times for gravity die casting are shorter than for the sand casting process leading to larger quantities of castings produced per unit time. Surface finish and internal quality (particularly pertaining to porosity) are also better using the GDC process. Improvements to both product quality and process productivity can be brought about through improved die design. These include developing more effective control of the die filling and die thermal performance.

Numerical simulation offers a powerful and cost effective way to study the effectiveness of different die designs and filling processes. For such simulations to be useful, their accuracy must first be assessed. There are a number of available software packages for casting simulation and analysis. These packages are grid-based and employ the volume-of-fluid method. In the die casting community, a popular commercial software package for simulating mould filling is MAGMAsoft and Smoothed particle hydrodynamics (SPH) is a Lagrangian method (Monaghan, 1992) and does not require a grid. It is suited for modelling fluid flows that involve droplet formation, splashing and complex free surface motion.

The simulation will describe the casting process by using volume of fluid (VOF) model integration with the solidification model in Fluent. A numerical optimization technique based on gradient-search is applied to obtain an optimal design of a typical gating system used for the gravity process to produce aluminum parts. Casting processes involve filling of molten metal in a mould and its solidification by withdrawal of heat. Filling and solidification involve rapidly growing metal/air free surface and liquid/solid interface within the solidifying domain, which makes the overall process experimentally difficult to visualize. Therefore, use of numerical simulations to analyze and control the solidification parameters related to fluid flow and heat transfer is desirable. This analysis is very useful to improve the quality of the casting.

One of the key elements to make a metal casting of high quality is the design of a good gating system. The gating system refers to those channels through which the metal flows from the ladle to the mold cavity. The use of a good gating system is even more important if a casting is produced by a gravity process. If poor gating techniques are used, invariably, lower casting quality is achieved, because of damage on the molten metal received during the flow through the gating system .It could be even worse, if the molten material is a sensitive metal for receiving damage during the filling, because of dross and slag formation.

The aluminum and their casting alloys are considered in this category. Aluminum alloys are very reactive to oxygen and form an oxide, Al_2O_3. When flow is smooth, this oxide tends to form and remain on the surface of the stream. However, when flow is turbulent, the oxide goes into the molten metal stream and may carry gas or air bubbles with it. The oxides remain on the turbulent flow without flotation, because their densities are similar to aluminum. Then, to avoid damage to the molten aluminum, the gating system must be designed to eliminate the air by avoiding conditions which permit aspiration due to formation of low pressure areas. Keeping the speed of the molten aluminum below of 0.50 m/s and a smooth stream is equally important.

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In order to achieve a good gating system design, it is necessary to start following basic principles. Molten metals behave according to fundamental hydraulic principles .Applying those fundamentals to the design of the gating system can be an advantage. The hydraulic factors that affect the flow of molten metals are: (a) Bernoulli's Theorem, (b) Law of Continuity, (c) Momentum Effects, (d) Frictional Forces, and (e) Reynolds Number. In the past decades some equations based on empirical relationships have been derived and used to design a gating system after applying these relationships, a gating system of questionable quality is obtained. Typically modifying the mold geometry by applying trial-and-error approach, a better gating system is obtained. However, this trial-and-error approach costs time and money. The aim of this project is to investigate the effects of gating system on mould filling in casting process and to formulate the alternative procedure to optimize the gating system with the use of computer aided numerical simulation techniques.

MAGMAsoft

MAGMAsoft is a 3D solidification and fluid flow package used in the die casting industry to model the molten metal flow and solidification in dies. MAGMAsoft employs the finite difference method to solve the heat and mass transfer on a rectangular grid. It is a useful tool for simulating molten metal flow in a permanent mould since it can provide useful information aboutthe filling pattern. It also produces reasonably accurate data on casting-related features such as premature solidification,air entrapment, velocity distribution, runner and gate effectiveness. MAGMAsoft, however, has some limitations. The rectangular grid artificially introduces staircases along curved and sloping boundaries and the VOF formulation for modeling the free surfaces leads to artifical diffusion and mass conservation problems in these region.

Computational Fluid dynamics (CFD)

Computational fluid dynamics, usually abbreviated as CFD, is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. With high-speed supercomputers, better solutions can be achieved. Ongoing research yields software that improves the accuracy and speed of complex simulation scenario.

The fundamental basis of almost all CFD problems are the Navier–Stokes equations, which define any single-phase (gas or liquid, but not both) fluid flow. These equations can be simplified by removing terms describing viscous actions to yield the Euler equations. Further simplification, by removing terms describing vorticity yields the full potential equations. Finally, for small perturbations in subsonic and supersonic flows (not transonic or hypersonic) these equations can be linearized to yield the linearized potential equations.

THE EXPERIMENTAL SETUP

The overall geometry of the casting—a simple plate with a simple bottom-gated running system (and no feeder)—is depicted by Figure 1 and Table I. The mold was made from 60 AFS-grade washed-and-dried silica sand, bonded with 1.2 wt.% phenolic urethane resin (Ashland Pepset). This is a widely used molding material, and it was hoped that good material properties would be available. The choice of a sand mold assisted the viability of analysis by x-ray radiography and simplified computation to some extent because i ts high permeability to air would reduce the back pressure to a minimum due to entrapped mold gas. The liquid metal used was 99.999% aluminum; again, this choice was made in order to obtain unambiguous and accurate material data.

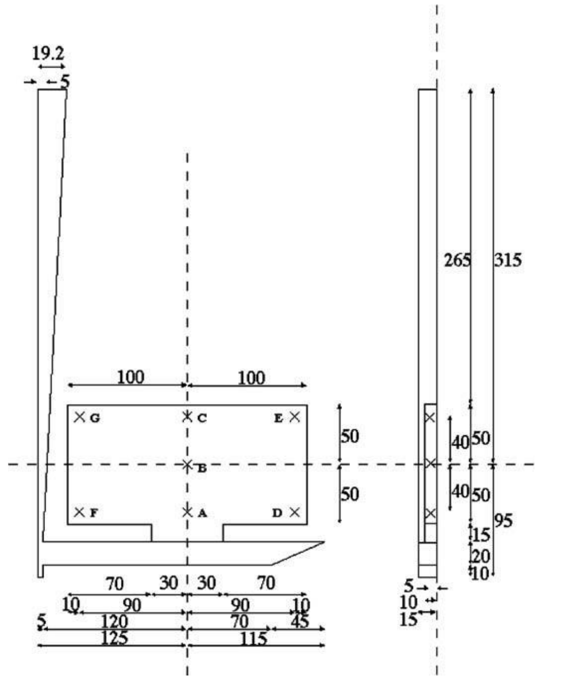

Figure 1:Dimensions of rectangular cavity (mm)

Axis	X	Y	Z
Sprue Entrance	15	19.2	—
Sprue Exit	15	5	—
Sprue Height	—	—	380
Well	15	5	10
Runner	15	240	20
Gate	10	60	15
Plate	10	200	100

Table I: Mold Dimensions are in mm

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Mold Material

The materials data for pure aluminum were taken In this from Metals Handbook, Rolls Royce, MagmaGmbh, and others.. These were a wide freezing range, which indicated that the data applied more accurately to commercially pure aluminum (99%) than the pure material intended for the experiment. the viscosity of liquid aluminum, which was quoted as a number (4×10^{-6}) without units. Smith ells Metals Reference Book gives the dynamic viscosity of pure aluminum at the freezing point as 1.3×10^{-3} Pa ·s and its density as 2.385×10^{3} kgm^{-3}. This yields a kinematic viscosity of 0.55 x 10-6 m^2/s.

X-Ray Radiography

Mold filling was observed with a 160 kV x-ray source (1.5 mm diameter) equipped with an image intensifier. Recording was performed using a VHS 50 Hz recorder. Pouring in the lead-lined cabinet was carried out remotely, outside the cabinet, by an operator viewing the pour via a closed-circuit television camera.

The instant when the stopper was lifted was designated as time zero. Subsequently, x-ray video frames were taken at 0.02 s intervals during filling. The experiment was repeated several times. In Figure 2, three sequences are shown. The figure presents video excerpts at 0.25 s intervals during the filling of three separate castings to ascertain the degree of reproducibility of the pour. The researchers were careful to ensure that the experimental conditions in e ach case were reproduced as exactly as possible. The only difference in the sequences is that the geometry of the view was changed slightly so as to see the sprue on one occasion and the ingate area and end of the runner on the other occasions.

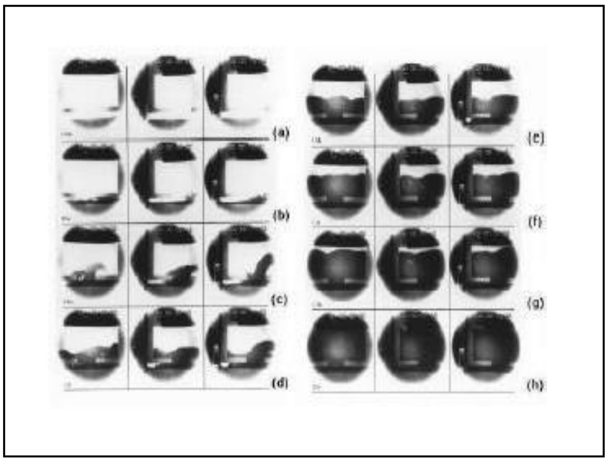


Figure 2. Three experiments run on the real- time x-ray unit to compare the progressive filling of the mold: (a) 0.24 s after stopper removal, (b) 0.5 s, (c) 0.74 s, (d) 1.0s, (e) 1.24 s, (f) 1.5 s, (g)1.74 s, and (h) 2.0 s.

Problem Definition:

The physical system for the present work consists of a rectangular mould of height 100 mm and width 200 mm. A schematic representation of the physical system is shown in Fig 3. Aluminium enters through the mould through the sprue.

In this work the runner depth (ZL) and slope of the gate (CX) are varied and its effects on the mold filling is to be studied. After doing various analysis the optimum values are find out using optimization technique by using fuzzy logic.

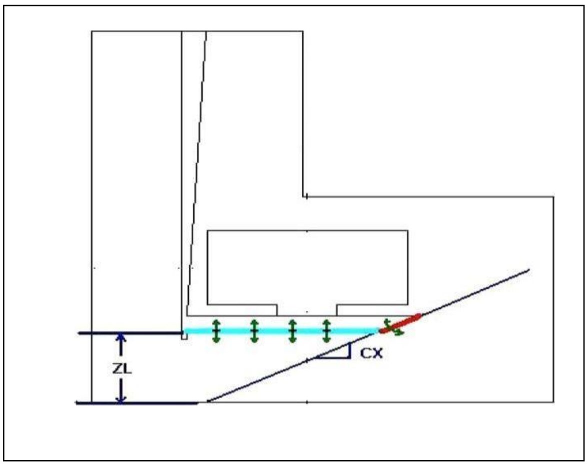
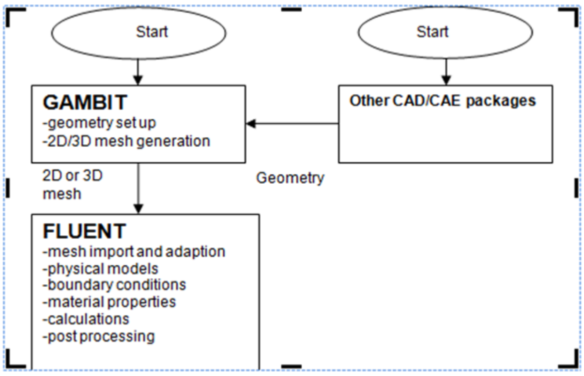


Figure 3. Gate design parameters ZL and CX

METHODOLOGY

In all of these approaches the same basic procedure is followed.

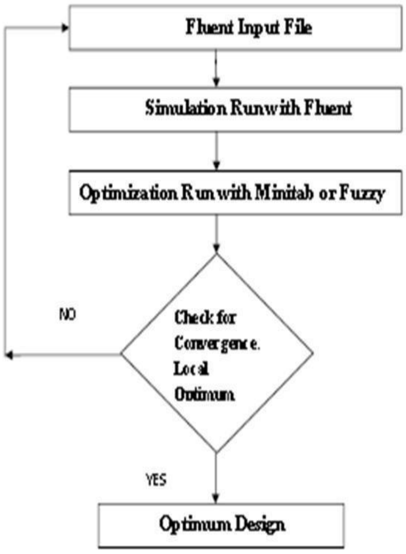


During preprocessing,

The geometry (physical bounds) of the problem is defined. The volume occupied by the fluid is divided into discrete cells (the mesh). The mesh may be uniform or non-uniform. The physical modeling is defined – for example, the equations of motion + enthalpy + radiation + species conservation Boundary conditions are defined. This involves specifying the fluid behaviour and properties at the boundaries of the problem. For transient problems, the initial conditions are also defined. The simulation is started and the equations are solved iteratively as a steady-state or transient. Finally a postprocessor is used for the analysis and visualization of the resulting solution.

Procedure for Optimization

After post processing the validation has done with the experimental work as shown in fig no 6.



Optimization model description

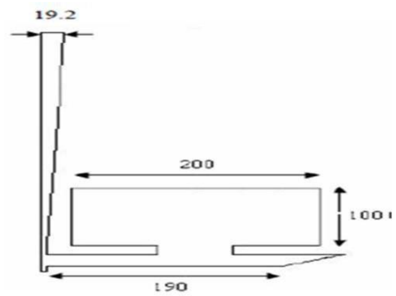


Figure no:4

For the present problem, the following formulation was used.

Design variables:

ZL_- runner depth (mm),
CX -_ slope on the tail(mm).

Parameters:

ZLl -_ lower limit of the runner depth (mm),
ZLu- _ upper limit of the runner depth (mm),
CXl -_ lower limit of slope on the tail(mm),
CXu -_ upper limit of slope on the tail(mm).

Auxiliary variables:

tci -_ filling time of element i of the runner; (s),
tej -_ filling time of element j of the ingate (s),
V xj -_ x-component of the aluminum velocity in the jth ingate element; (m/s),
V yj -_ y-component of the aluminum velocity in the jth ingate element; (m/s),
V zj -_ z-component of the aluminum velocity in the jth ingate element (m/s),
Vj _- objective function that represents the aluminum velocity at the jth ingate element.

Formulation:

Minimize Vj (ZL, CX) = $\sqrt{Vxj^2 + Vyj^2 + Vyz^2}$

Subject to:

- **tci $\leq$ tej**
- **ZLl $\leq$ ZL $\leq$ ZLu**
- **CXl $\leq$ CX $\leq$ CXu**

Design of Experiments (DOE):

For the experimental design (DOE), an L9 array were used. The complete set of analysis included 09 executions using 2 factors at 3 levels each ($3^2 = 09$). The values used for the starting solution values of the two design variables and the step size parameter are shown in Table no 2.

Analysis No	ZL	CX
1	9.5	0.3
2	9.5	0.9
3	9.5	1.5
4	10.25	0.3
5	10.25	0.9
6	10.25	1.5
7	10.9	0.3
8	10.9	0.9
9	10.9	1.5

Table no 2.

Design of experiments has conducted.Out of the 9 values the optimum gate design has obtained through optimization technique. For that fuzzy logic used by writing rules for getting effective velocity at the ingate.

Model I

Experimentally at selected time instances are compared. In the experimental images, the number at the bottom left corner is the time in seconds. The filling process for Model 2 is somewhat similar to that of Model 1 in that the early part of die filling is dominated by sloshing free surface wave motion. This sloshing motion is damped after a certain time. We thus restrict our discussion to the early part of the die filling when the process is much more dynamic.

At 0.24 s, the large rectangular section of the cavity is just starting to fill. In that simulations shows the red color is metal,blue color is air.

At 0.5 s, the metal reached to the ingate at both experimental and simulation condition.

At 0.74 s,the amount of metal filling has entered into the cavity with high velocity.

At 1.24 s, tbe amount of metal is filling and spread over horizontally whereas vertical direction of flow in fluent.

At 1.74 s. the flow of metal almost completed has turbulent flow at both condition.
At 2 s,the metal gets filled completely inside the rectangular cavity in both models.

RESULTS

For the effective mold filling and optimized gating design can be achieved through CFD package. Then the Design of experiments conducted with L9 array and number of trials taken then its applied to fuzzy logic by writing rules for 9 values at low,medium and high level condition.

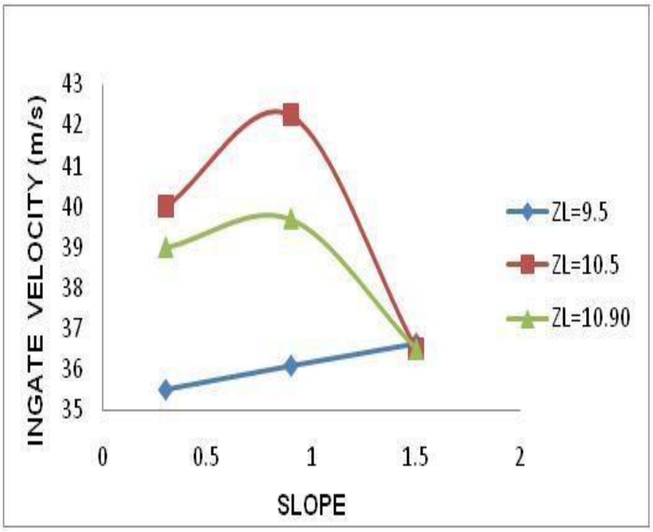


Figure:5

The optimized value of inlet velocity at an average value of 39.4m/sec.

The optimum value of runner tail slope is 0.85 mm .
The optimum value of runner depth is 10.2mm.

CONCLUSION

In this paper,
. Apart from the trial and error approach, this numerical simulation results will give effective mould filling and solidification. The experiment and both numerical methods is good with each being able to predict the overall structure of the filling process.
- The simulation results of cavity filling are validated with the experimental work by the use of Fluent.
- Design of experiments conducted with L9 array.
- Condition followed that the time of filling of the runner should be first than the ingate filling time. Otherwise the bubble will form.
- The optimum velocity has attained to the ingate for an effective mold filling. Further the solidification area can concentrate for the change of heat transfer through MAGMA or Fluent.
- MAGMA software is more reliable and used in big industries but the same time the software is too costly to use. Such that small scale industry Fluent can. Use.
- Further experiment can conduct with the optimized value and compared with the simulation work.

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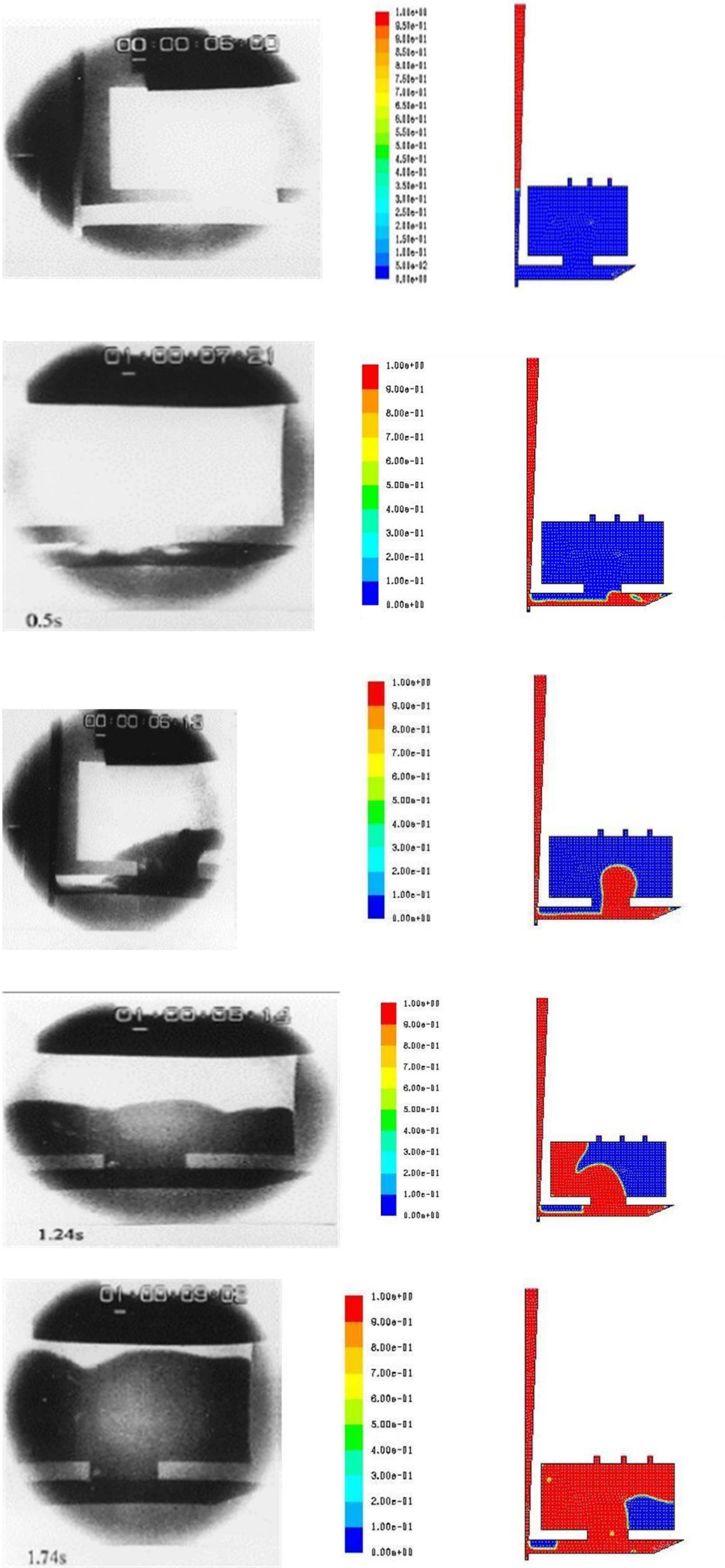

Figure 6: Filling of Model 1. Left: Experiment . Right: Fluent Software