Temperature Losses in Cups of Tilt-Poured Permanent Molds

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ABSTRACT

Tilt-pour permanent mold casting is a process where a cast iron or steel mold is filled by tilting it from the horizontal to the vertical position; the purpose is to reduce the turbulence which takes place when the mold is "gravity filled" in a vertical position. The liquid aluminum is first poured into a cup that will deliver the liquid metal to the mold as the cup-mold assembly is tilted; the cup is generally emptied when a tilt angle of 45 degrees is reached; the mold continues its motion until it is vertical, this position is kept until the casting and gating are fully solidified.

The temperature of the metal poured into the mold is lower than that of the metal poured in the cup by an amount that will be called the temperature loss in the cup. This loss depends on factors such as the amount of metal poured, the tilt speed and the number of cycles per hour. It is rarely considered when modeling the thermal history of the process; one may sometimes subtract more or less arbitrary number of degrees to the temperature of the metal poured into the cup. The purpose of this paper is to evaluate these temperature losses via thermal modeling; the validity of these predictions will be tested on two castings involving widely different conditions in terms of the amount of metal poured, filling time and number of castings poured per hour.

Keywords: temperature losses, permanent mold casting, tilt pour cups, heat transfer modeling

INTRODUCTION

Tilt-pour casting is an enhancement of the gravity permanent mold process; it allows mold filling with less turbulence, avoiding detrimental oxides to form at a much lesser capital investment than the low-pressure process. Under certain conditions, tilt-pouring allows for filling the mold cavity from the top, an extremely favorable situation for feeding the casting, especially at low filling velocity. Figure 1 illustrates the tilt-pour process where a 14 kg casting (18 kg/40lb poured) is produced at a rate of 12 castings/h. The pouring temperature is 718C (1325F) and the tilt time from 0 to 90 degrees is 20 seconds; it means that the filling time is 10 seconds as the cup empties when the tilt angle is 45 degrees. Ejection takes place after 5 minutes, when the alloy has solidified enough to withstand the pressure of the ejector pins.

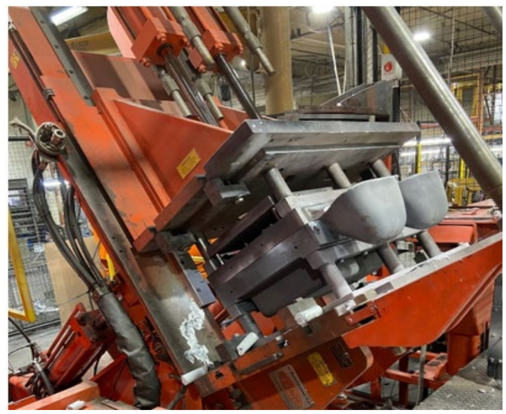

Figure 1. A tilt pour machine equipped with 10 kg (22lb) size cups. (Artwork courtesy of Paber Aluminium.)

The filling velocity should always be less than 0.5m/s to avoid breaking of the oxide protective layer, thus preventing further oxidation of the metal.[1] The metal velocity can be considerably reduced if the filling takes place between, -20 and +20 degrees, as done in the original Durville process, illustrated in Figure 2.

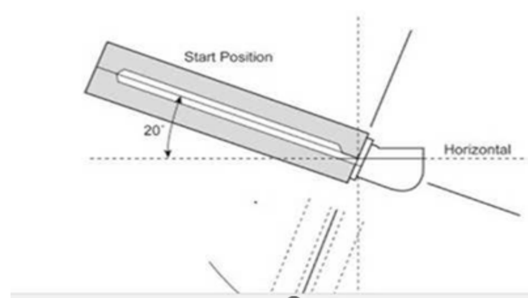

Figure 2. The Durville process with minimal turbulence.

In the Durville process, the filling starts with the liquid moving upwards; it is well under way when the mold is in the horizontal position, so that the velocity is always less than 0.5 m/s until the end of filling. A very picturesque “hands-on” description of the Durville process principles is available in a video.[2] The author laments the fact that the tilt-pour machines available on the market are “all wrong” for starting with the mold in a horizontal position, which results in velocities well above 0.5m/s at the end of filling. Stahl Specialties has been a pioneer in the production of tilt-poured castings in Kingsville (Mo), as early as 1961.[3]

SCOPE OF THE PRESENT WORK

In gravity permanent mold casting, the pouring temperature is virtually the temperature of the metal in the holding furnace. In the case of tilt-pouring, there is a drop in temperature due to the intermediate pouring of the metal into a relatively cold cast iron cup, which depends on how cold the cup is, and how long the liquid alloy remains in the cup (i.e., the duration of the filling). As a first approximation, say that the temperature drop increases with slower filling, resulting in a lower number of parts produced per hour and higher weight of cup to weight of liquid metal ratio. The purpose of this work is to evaluate these losses for various cup sizes for bulky and rangy castings for the tilt times of 20 and 40 seconds (0 to 90°). This will be achieved by modeling filling and solidification after a dynamic thermal equilibrium has been reached (i.e., after 5 cycles).

MODELING PROCEDURE

To select representative conditions for the modeling, a survey in three partner foundries (#1, 2 and 3) was carried out and the following information was collected:

a) Castings poured with one cup ranged from 5 to 8 kg/12 to 18lb (total metal poured) in the three foundries, for solidification times from 2 to 5 minutes.

b) Except for foundry #3, most castings were poured with two cups; in this case, the casting weight varied from 16 to 90kg (35 to 200lb) for foundry #1, with corresponding cup sizes from 8 to 45kg (18 to 100lb); the solidification times varied from 7 to 16 minutes. The data for foundry #2 was 7 to 25kg (15 to 55lb) castings solidifying in 3 to 8 minutes.

Therefore, it was decided to model three sizes of cups: 5kg, 15kg and 30kg (12, 33 and 66lb), for solidification times attuned to the cup sizes.

As an example, additional results from the modeling for the following conditions are:

- Cup size of 15kg (33lbs) poured as a 25mm (1in) thick plate, for a 0 to 90° tilt with times of 20 and 40 seconds.

- Most commercial cups available are shaped so that they empty when the tilt angle is 45°; consequently, 0 to 90° tilt times of 20 and 40 seconds correspond to filling times of 10 and 20 seconds.

The thermal properties of aluminum A356 and cast iron were those from the commercial software database and workbook,[4] as was the liquid metal-cup heat transfer coefficient (1200W.m^{-2}.C^{-1}).

The external heat transfer coefficient (HTC) to the atmosphere was calculated from Stefan’s law of thermal radiation[5] and empirical relationships describing the heat transfer by convection from plates;[6] the resulting external HTC as a function of the surface temperature is shown in Figure 3.

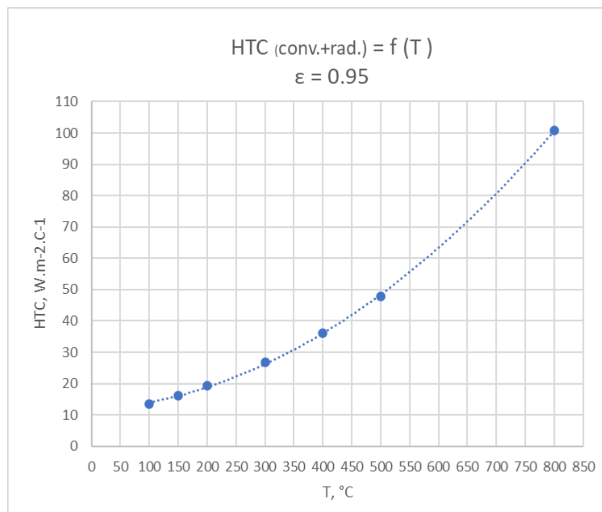

Figure 3. External heat transfer coefficient (HTC) from the mold and cup surfaces.

The model in shown in Figure 4 for a plate 495 x 300 x 25mm (20 x 12 x 1in.), with a square riser 75 x 75 x 300mm (3 x 3 x 12in.). The mold walls are 50mm (2 in. thick. The total metal poured weighs 15kg (32lb) and the cast iron cup 10kg (22lb).

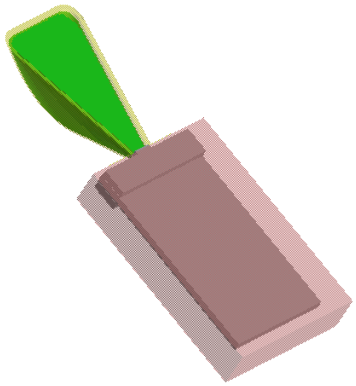

Figure 4. Model of the 15 kg (32lb) casting.

The initial temperature of the mold was set to 350C (660F), that of the cup 150C (300F) and five cycles were run to reach a dynamic thermal equilibrium. Ejection took place when 100% of the casting and riser were solidified and the mold remained opened during 90 seconds within the whole cycle.

Figure 5 shows the temperature distribution in the liquid A356 alloy poured at 720C (1328F) after 5s and 10s in the 20s tilt pour, while Figure 6 shows the situation for the 40s pour, 10s and 20s into filling.

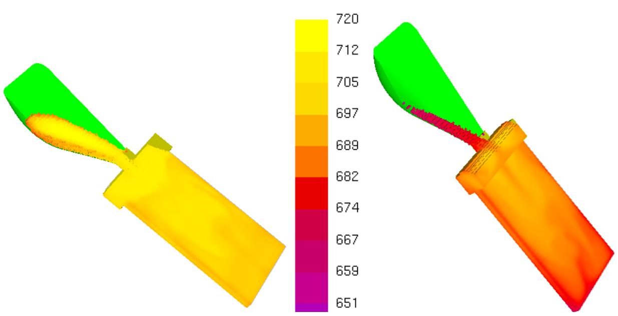

Figure 5. Temperature (°C) after 5 and 10s (20s tilt run).

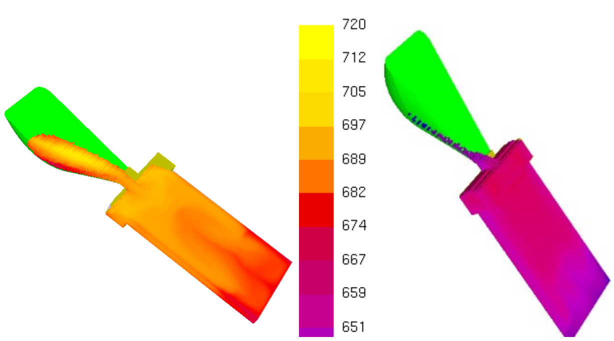

Figure 6. Temperature (°C) after 10 and 20s (40s tilt run).

The modeling allowed to plot the temperature loss at the entrance of the mold, as shown in Figure 7. Quite expectedly, the loss was more important for the 40s tilt, as the residence time of the liquid in the colder cup is longer. However, a very important factor does not appear in the present results, because it is virtually the same in the two instances; this is the cycle time, which mainly depends on the solidification time: 7.9 min and 6.8 min for the 20s and 40s tilt runs, respectively.

An average temperature drop is obtained by the integral of the variable temperature loss, ΔT (p) over the percent filled, p:

$$\Delta T_{mean} = \int T(p).dp \text{ from p=0 to p=100}$$

Which is represented by the surface area under the curves of Figure 7. We thus determine average temperature drops of 16.4°C (30°F) and 23.4°C (42°F) for the 20s and 40s tilt times.

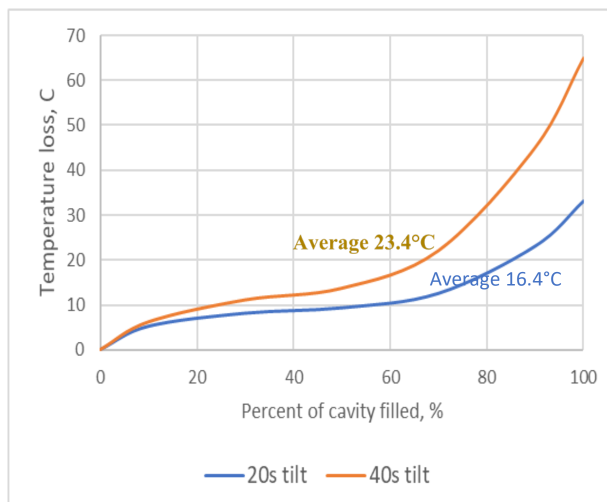

Figure 7. Temperature loss at the entrance of the mold vs. percent of cavity filled.

The filling rate could also be plotted as shown in Figure 8. The red line represents a constant flow rate hypothesis for a 40s tilt. The actual flow rate is close to the constant flow rate hypothesis until 20% of the cavity has been filled; then, it is smaller until 70% of the mold is filled; above 70% filled, the actual flow rate is much higher than that of the constant flow rate hypothesis.

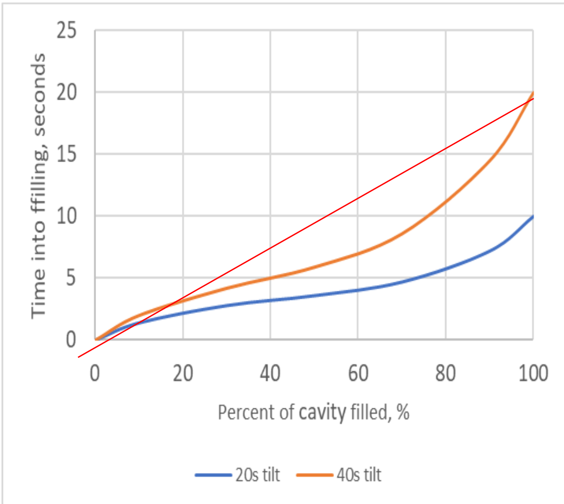

Figure 8. Tilt pouring rate versus constant rate (red line).

If the casting was larger than the 25mm (1in) thick plate modeled, the solidification time and the cycle time would be longer, resulting in a colder cup at the end of the cycle and a possible increased temperature drop.

Figure 9 (a & b) shows the predicted variation of the temperature at the bottom of the cup for tilt times of 20s and 40s, corresponding to filling times of 10 and 20 seconds. The temperature of the 40s tilt cup is higher because it remains in contact with the hot liquid metal during 20s instead of 10s for the 20s tilt run; the liquid entering the mold is consequently colder, which explains the shorter cycle time of the 40s tilt run. The cycle time is 9.2 min for the 20s tilt run and 8.4 min for the 40s tilt run after the thermal dynamic equilibrium has been reached, i.e., five cycles.

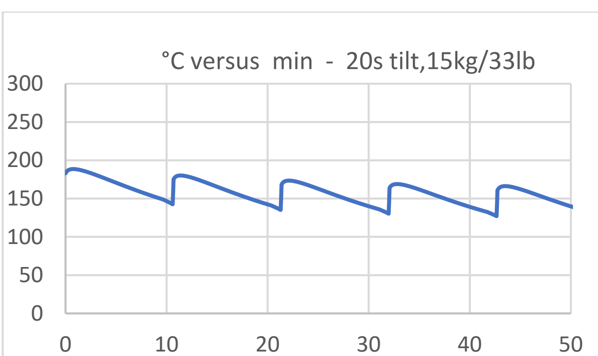

Figure 9a. Temperature at the bottom of the cup, 20s.

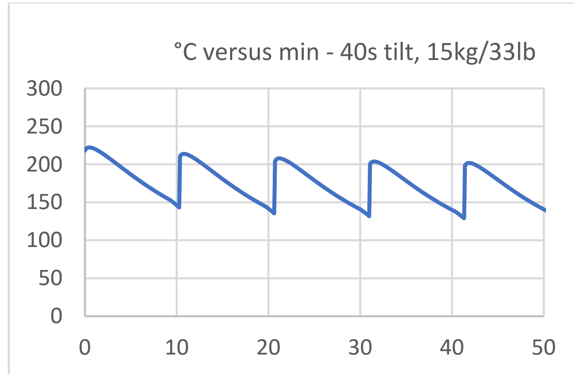

Figure 9b. Temperature at the bottom of the cup, 40s.

Ejection times after 5 cycles are 7.7 min and 6.9 min for the 20s and 40s tilt conditions respectively. The ejection time is longer because the metal entering the mold is hotter in the 20s tilt, hence the longer solidification and ejection times.

PREDICTED TEMPERATURE LOSSES DURING TILT MOTION IN 5, 15 & 30kg (12, 32 & 62lb) CUPS VS CYCLE TIMES

The same analysis done on the 15kg/32lb cup was carried out on 5kg and 30kg/12 and 66lb cups, for different cycle times.

The small cups are relatively heavier: 10kg/22lb of cast iron for the 5kg/12lb cup size, 20kg(/4lb for the 15kg/33lb size, and 30kg/66lb for the 30kg/66lb size. The molds were naturally cooled.

For a cup of given size, the temperature loss is expected to increase with the tilt time, because of the longer contact time between the liquid metal and the colder cup; the temperature loss is also expected to increase with the duration of a cycle because the cup will cool at a lower temperature before being filled again. This is indeed what the results of the analyses indicate for cup sizes of 5, 15 and 30kg (12, 33 and 66lb) shown in Figure 10.

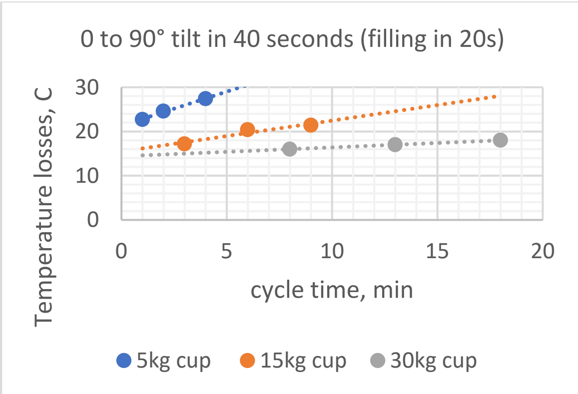

Figure 10. Temperature loss as a function of cycle time.

It should be stressed that the above temperature losses assume that the filling of the cup is instantaneous. In reality, the temperature drop will be less because the cup will have been preheated during the time necessary to fill it, which can be considerable if several hand ladle contents are necessary to fill the cup. Hence the graph in Figure 10 would give a maximum value of temperature losses during the tilt motion.

EXPERIMENTAL STUDY OF LOSSES IN CUPS DURING FILLING OF CUPS IN CASTINGS OF 18 & 60kg (40 & 132lb)

The temperature losses during the tilt motion considered so far must be distinguished from the losses during the filling of the cup which may be much larger especially for 20kg (44lb) up to 50 kg (110lb) cup, where 2 and 5 hand ladle contents are necessary to fill the cups, respectively. These temperature losses have been measured on dual cup tilt-pour machines for an average size casting (urban bicycle-shared stand): 18kg (40lb) poured, 9 kg (20lb) of metal in 10kg (22lb) cups, and for a large casting (compressor housing): 60 kg (132lb) poured, 3 hand ladle contents poured into each of two 30kg (66lb) cups by 2 pourers.

The temperature of the metal was measured in the furnace and in the cup at the end of its filling with a type K thermocouple, and at the bottom of the cup before filling and at the end of the 90° tilt motion, with a "handgun type" radiation pyrometer.

These measures were made during a stable production run, over four cycles and the results were averaged.
The time into the cycle was measured from the beginning of cup filling; the temperature at the bottom of the cup was measured after cup filling, at the beginning and the end of the tilt motion.

The results are shown in Table 1. The steel hand ladles used to fill the cups were thoroughly preheated in the liquid aluminum bath before scooping, so that the loss in temperature between the furnace and the cup was very small. However, the liquid metal loses temperature at the contact with the cup, even more so if the start of the tilt motion is delayed: the start of the tilt motion took place 5 seconds after the beginning of cup filling for the 18kg (40lb) casting where one hand ladle content was sufficient to fill each cup; it was 20 seconds for the 60kg (132lb) casting, 3 hand ladle contents being necessary to fill each of the two cups. Hence, at the beginning of the tilt, the temperature loss is 772 - 748C = 24°C (43°F) for the medium size casting and 733 - 692C = 41°C (74°F) for the larger casting. These temperature drops must be added to those occurring during the tilt motion, losses which were previously determined by modeling and plotted in Figure 10.

Table 1. Experimental Results of Temperature Measurements in Liquid Metal and on Cup(Medium- and Large-size Castings)

Medium size casting18kg/40lb 2x10kg cups filled with 10kg/22lb hand ladles. Bottom of cup Kao-wool insulated. 6.1 min cycle time	Time, s	Temp. of liquid metal, °C/°F	Temp. at bottom of cup, °C/°F
Cup filling begins (one ladle content)	0.00	772/1428 ((furnace temp.)	351/664
Tilt motion begins	5	748/1378 (24/53 loss)	
Tilt motion ends	25	-	415/780

Large casting (60kg/132lb) poured. 2 x 30kg cups filled with 10kg/22lb hand ladles. Bottom of cup Kao-wool insulated. 11.6 min cycle time	Time, s	Temp. of liquid metal, °C/°F	Temp. at bottom of cup, °C/°F
Cup filling begins (3 ladle contents)	0.00	733/1351 (furnace temp.)	345/653
Tilt motion begins	20	692/1278 (41/90 loss)	
Tilt motion ends	60	-	426/800

MODELING THE CUP TEMPERATURE DURING FILLING FOR 10kg/22lb & 30kg/66lb CUPS & COMPARISON WITH EXPERIMENTAL RESULTS

The 3D model of the cups is shown in Figure 11 based on the shape of the most popular cup size.

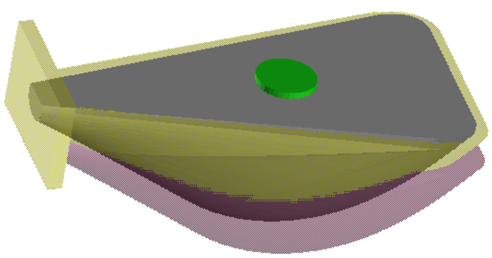

Figure 11. Shape of pouring cup model.

The evolution of temperature in the liquid during the filling of the cup was modeled as illustrated in Figure 12 for the 30kg/66lb cup. The bottom of the cup was insulated, as represented by the purple material in Fig. 11.

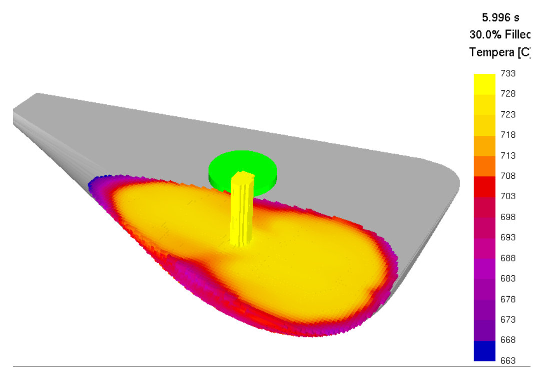

Figure 12. Modeling the filling of the cup during tilting.

The filling of the 30 kg/66lb cups (3 hand ladle scoops) was assumed to be continuous over the 20 seconds total fill time. The distribution of the temperature at mid height at the end of the fill is shown in Figure 13 (a& b).

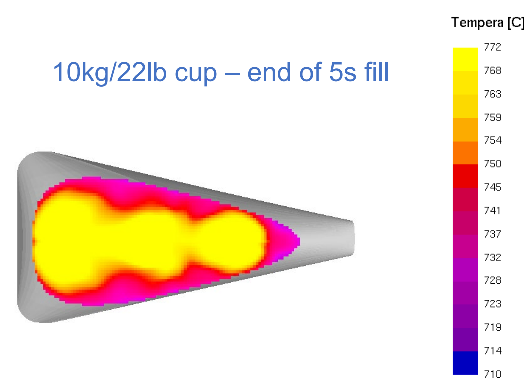

Figure 13a. Temperature at mid height (at end of 5S fill).

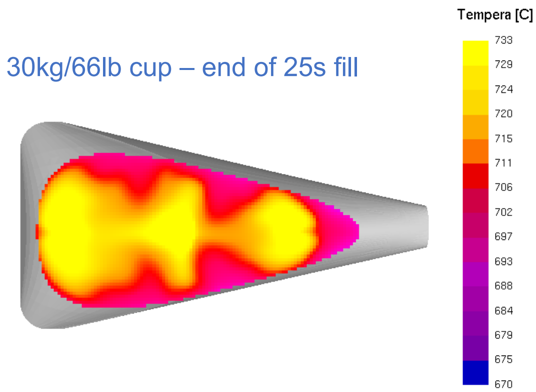

Figure 13b. Temperature at mid height (at end of 25S fill).

The temperature at the end of the filling of the cup is not uniform which entails that the measures of the liquid metal temperature in the cup will exhibit a scatter mitigated by vigorously moving the thermocouple tip inside the bath for a few seconds.

Five cycles were run to reach a reach a dynamic thermal equilibrium, the predicted average temperature at the end of filling was determined by averaging the nodes temperatures. An average temperature of 753C (1387F) was determined for the 10kg (22lb) cup for a temperature loss of 772 - 753C = 19°C (35°F) at the end of one 5s fill.

Similarly, a predicted average temperature of 701C/1294F was obtained at the end of the 20s fill of the 30kg (66lb) cup, hence a 733 - 701C = 32°C(58°F) temperature drop. These predicted results (19°C and 32°C/35°F & 58°F) are about 20% less than the experimental results (24°C and 41°C/ 43°F &74°F).

PREDICTED RESULTS FOR VARIOUS CUP SIZE & CYCLE TIMES

The exercise made in the previous chapter can be done for different cup size and cycle times. The 10kg, 20kg and 30kg (22, 44 and 66lb) cups are filled with 1, 2 and 3 hand ladle contents (a.k.a. "scoops"). Assuming it takes 5 seconds to empty the hand ladle into the cup and 10s are necessary for the back-and-forth trip from the furnace to the casting machine, the filling time (again, the filling is assumed to be continuous) are 5s, 15 s and 25s for the 10kg, 20kg and 30kg/ 22, 44 and 66lb cups respectively. When this exercise is done, the predicted results of Table 2 are obtained.

The hand ladles are assumed to be fully preheated to the furnace melt temperature so that no temperature loss takes place between the furnace and the cup.

Table 2. Predicted Temperature Losses During Cup Filling for Different Cup Sizes and Cycle Times

	Temperature drop, °C/°F		
Cycle time min	10 kg cup (1 scoop) 5s fill	20 kg cup (2 scoops) 15s	30 kg cup (3 scoops) 25s
5	11./20	29/52	39/70
10	13/23	37/67	50/90
20	15/27	42/74	56/101

The bulk of the heat is lost to the cast iron cups during their filling, an amount of heat which is then transferred to the atmosphere during one casting cycle.

An additional temperature drop will occur during the tilt motion, which was considered earlier (Figure 10); it will however be less than that given in Figure 10 because the cup will have been preheated during its filling, which was not the case for the results of Figure 10 where the filling was assumed to be instantaneous.

CONCLUSIONS

In the permanent mold tilt pour process, the loss in temperature between the furnace and the mold is substantial and should be considered when modeling the filling of the mold and the subsequent solidification of the casting. This loss may be divided into parts:

- The loss during the filling of the cup, which is usually the greatest, especially if several trips back-and-forth from the furnace to the machine are necessary. This loss is given in Table 2 as a function of the size of the cup and the cycle time for a 10s back-and-forth trip from the furnace to the casting machine; the hand ladles are assumed to contain 10kg (22lb) of melt and to be fully preheated to the furnace melt temperature.
- The loss during the tilting of the mold from 0 to 45 degrees for the geometry of the most common cups. It will increase with the tilting time and with smaller cups as shown in Figure 10.

The purpose of this paper was to raise awareness about the importance of the temperature losses in the tilt-pour casting process as compared to gravity casting. If the predicted losses during the tilt motion given in Figure 10 are useful, those given in Table 2 may more reliably be measured on the shop floor; they will differ from those given in the table depending on the conditions in the foundry, namely:

- The distance from the furnace to the casting machine.
- The size of the hand ladle, generally 10kg (22lb).
- The more or less thorough preheating of the hand ladle before scooping the melt.

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