Experimental and numerical analysis of ladle teeming process

G. M. Mazzaferro[1], M. Piva[2], S. P. Ferro[1], P. Bissio[2], M. Iglesias[2], A. Calvo[2] and M. B. Goldschmit*[1]

In continuous casting, the molten steel is poured from the ladle to the tundish through a nozzle located at the bottom of the ladle. This process, however, must be stopped before the ladle is completely emptied to avoid slag carryover to the tundish. The amount of steel that remains unteemed in the ladle is usually significant, so steel plants are highly interested in studying different ways to improve the process. In the present work, experimental studies using water models and numerical simulations have been employed to analyse the conditions needed for vortex formation and investigate the influence of geometrical and flow parameters on the amount of wasted steel. Both experimental and numerical results lead to the conclusion that no vortex formation is expected to take place during ladle drainage under industrial conditions.

Keywords: Continuous casting, Ladle teeming, Modelling

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Introduction

During the continuous casting process, molten steel is poured from the ladle to the tundish through a nozzle located in an eccentric position in the ladle floor. A ladle is a vessel of generally cylindrical shape with a diameter of 2–3 m and a height of ~3 m. It contains between 100 1 and 200 t of liquid steel, which is drained through a 5–10 cm diameter nozzle.

Molten steel in the ladle is covered by a slag layer (whose thickness varies between 5 and 20 cm), which prevents its oxidation by air contact. As the draining process progresses, the interface that separates the steel from the slag eventually deflects towards the drainage nozzle and adopts the form of a 'funnel'. Funnel formation leads to slag carryover from the ladle to the tundish. Drainage is stopped when first traces of slag are detected in the nozzle, leaving a significant amount of steel (up to 3 t) unteemed in the ladle.

The funnel formation effect has been analysed by several studies,[1–7] generally based on experiments conducted via physical models where water is used instead of steel. In these experiments, water drainage from cylindrical or square cross-section vessels with flat horizontal floors haas been studied for various nozzle diameters (0·54–8 cm) and eccentricities (up to 0·7). The subjacent fluid dynamics of the phenomenon has also been analysed by several authors.[8–14]

According to the literature,[1–8] two different mechanisms can lead to deflection of the steel surface: vortex sink or drain sink.

Vortex sink is characterised by high tangential velocities in the neighbourhood of the nozzle (Figs. 1*a* and 2*a*) and can develop even with a high column of steel in the ladle. Vortex formation can take place in vessels where the fluid has significant initial tangential velocities, especially if the discharge nozzle is centred. The amount of liquid in the ladle when vortex sink reaches the nozzle depends on the initial rotational velocity and the nozzle eccentricity.

On the other hand, drain sink is characterised by radial flow (Figs. 1*b* and 2*b*), and develops in the last stage of the teeming process, when less liquid steel is left in the ladle. Drain sink is always present at the end of the process and does not depend on the previous formation of vortex sink. The height of the liquid column left unteemed in the ladle when drain sink erupts in the nozzle is approximately equal to the diameter of the nozzle. Drain sink eruption in the nozzle, unlike vortex sink eruption, leads to a significant proportion of slag carryover.[1,4,6]

Taking into account the above considerations found in the literature, it seems that, owing to nozzle eccentricity and the absence of preferred rotation sense, vortex sink is not expected to take place under general plant conditions. The amount of steel usually downgraded in plants due to slag carryover is consistent with this hypothesis.

In the present work, water model experiments were carried out to confirm the last assumption by estimating the probability of vortex formation in actual casting practice. Then, numerical simulations were conducted of an industrial ladle drainage process, with the focus on drain sink formation and the possible influence of ladle floor geometry. An analysis of experimental and numerical results is presented.

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[1] Centre for Industrial Research, FUDETEC, Dr. Simini 250, 2804 Campana, Argentina
[2] Porous Media Group, Engineering School, Universidad de Buenos Aires, Paseo Colón 850, 1063 Buenos Aires, Argentina

*Corresponding author, e-mail sidgld@siderca.com

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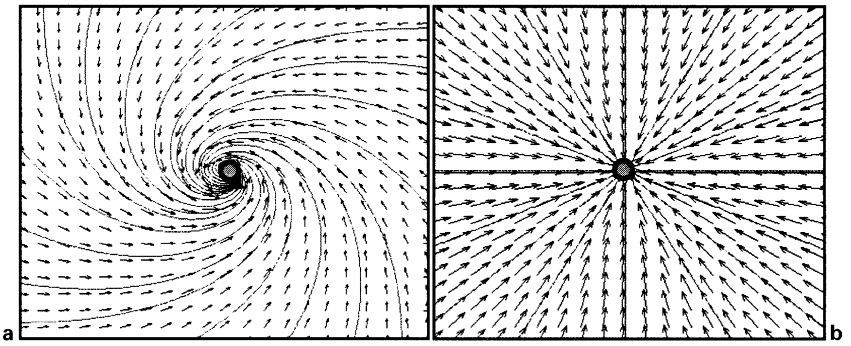
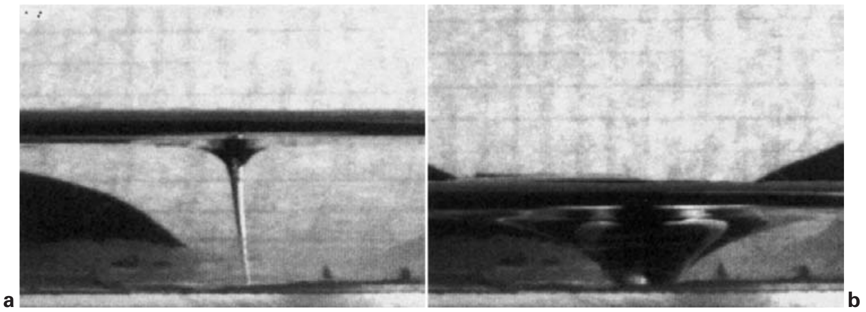


a vortex sink; *b* drain sink

1 Schemes of flow pattern and streamlines for given sink mechanisms



a vortex sink; *b* drain sink

2 Photographs of surface deformation owing to given sink mechanisms

Water model experiments

Water model experiments were carried out by the Porous Media Group at the Engineering School of Buenos Aires University.

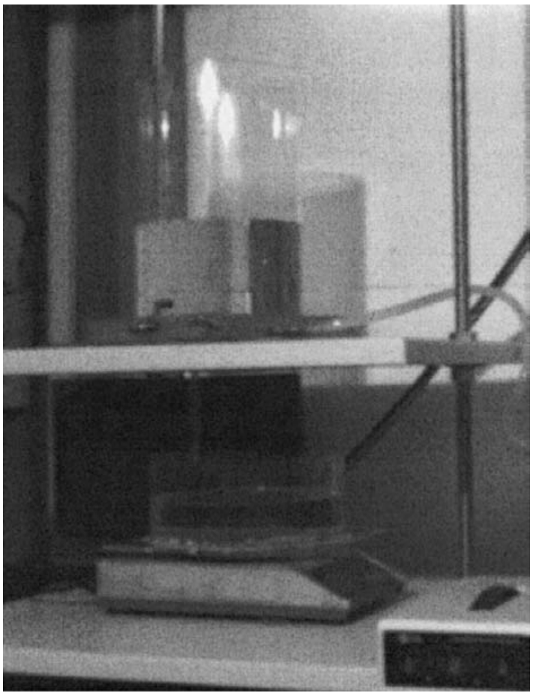
The experimental setup used to analyse the flow of water during the draining process is shown in Fig. 3. A cylindrical container of diameter $D=20$ cm was partially filled with water to a constant height H_0, through two tangential pipes located at opposite sides of the 2 container bottom and at 1 cm from the wall. This way of filling provided the fluid with the tangential velocity necessary to induce vortex formation. Water was drained through a nozzle of diameter $d_n=0{\cdot}5$ cm and length $h_n=10$ cm located at the bottom of the vessel and at a distance r_ε from its centre.

Once the filling process was concluded, the velocity field decayed with time until the fluid remained at rest. Hence, the initial velocity field could be selected according to the waiting time t_i between the end of filling and the beginning of drainage. Assuming that the flow field was essentially tangential and axisymmetric, the initial flow condition was characterised through V_θ, defined as the maximum initial tangential velocity measured at the free surface.

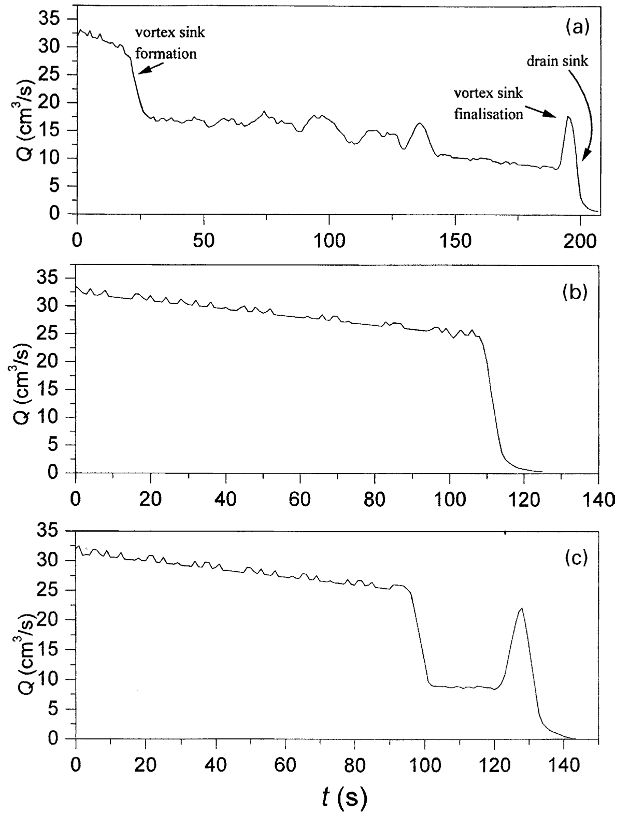
Once the nozzle was open the mass of water leaving the ladle m was collected in a second vessel where its weight was monitored as a function of time with a precision balance. In this way the flowrate at the nozzle output $Q=\mathrm{d}m/\mathrm{d}t$ could be obtained.

The critical height H_c, defined as the level of water in the ladle when air eruption in the nozzle took place, was analysed as a function of the nozzle eccentricity $\varepsilon=2r_\varepsilon/D$ and initial tangential velocity V_θ.

In Fig. 4*a* an example showing the time evolution of the flowrate Q through the nozzle is presented. The figure corresponds to the drainage of an $H_0=11$ cm water column through a centred nozzle ($\varepsilon=0$) and large initial tangential velocity, $V_\theta\approx2{\cdot}5$ cm s^{-1}. It can be seen that the initial flowrate $Q_i\approx32$ cm^3 s^{-1} decreased smoothly with time until $t=28$ s. In this period the free surface of the fluid remained almost flat except in the vicinity of the nozzle axis, where the formation of a small free surface depression (or dimple) was observed after a few seconds. The theoretical flowrate calculated



3 Water model for cylindrical ladle



a ε=0, large V_θ; *b* ε=0, small V_θ; *c* ε=0·5, large V_θ

4 Flowrate *Q* as function of time *t* for ladle drainage with given conditions of eccentricity ε and tangential velocity V_θ

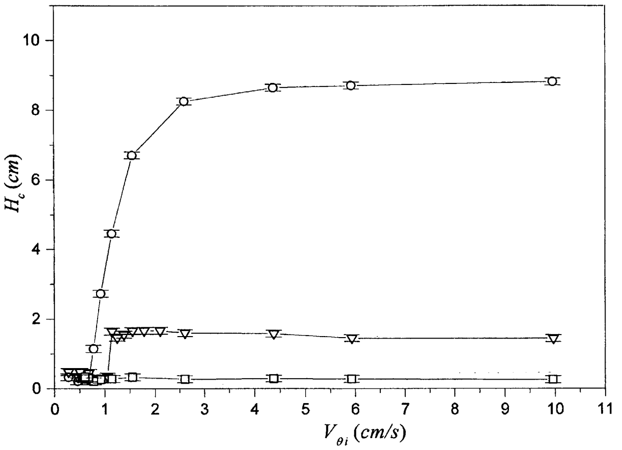
from the Bernoulli law was found to fit quite well to the experimental data, indicating the inviscid nature of the drainage process at this stage.

The abrupt drop in the flowrate at $t_c \approx 28$ s indicates the beginning of vortex sink. The critical height was H_c=8·6 cm while the drained percentage was ~22%. Simultaneously the free surface dimple evolved downwards to form a long vortex funnel, which went through the output producing the eruption of air in the nozzle. After this critical event the flowrate mean value decreased smoothly with fluctuations caused by the presence of air in the nozzle.

In the final part of the drainage, $t \approx 190$ s, it is observed in Fig. 4*a* that the funnel disappeared; the remaining circulation was not enough to sustain vortex sink and the free surface of the fluid became flat. This phenomenon occurred at $H \approx d_n$. The nozzle was again filled with water and the flowrate increased suddenly during a few seconds, producing significant drainage. Then, drain sink occurred at t=198 s.

In Fig. 4*b* a new example is considered with identical conditions as the previous case but with a much lower initial tangential velocity (much longer waiting time). In this case the initial circulation was not large enough to produce a vortex, and the ladle drained with the free surface almost flat until t=109 s when drain sink occurred. The drained percentage was ~85%.

To analyse the influence of nozzle eccentricity, experiments were conducted under similar conditions to those illustrated in Fig. 4*a* (H_0=11 cm and large initial tangential velocity) but with two different values of nozzle eccentricity: ε=0·5 and ε=0·9.



5 Critical height H_c as function of initial tangential velocity $V_{\theta i}$ for given values of nozzle eccentricity ε: circle symbols ε=0, inverted triangles ε=0·5, squares ε=0·9

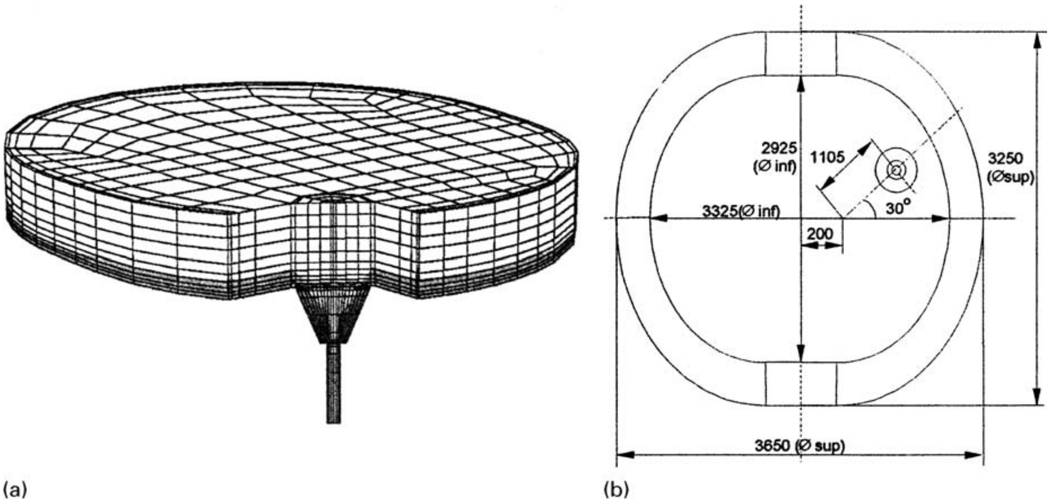
In Fig. 4*c* the results for ε=0·5 are shown, and it can be seen that a vortex developed at t=96 s. The critical height was H_c=1·6 cm and the drained percentage 86%. For ε=0·9 the flowrate evolution was similar to that shown in Fig. 4*c*, that is, no vortex was observed despite the considerable amount of initial circulation. Again, drain sink occurred at the end of drainage when $H \approx d_n$.

A complete set of results is presented in Fig. 5 where the critical height H_c is plotted as a function of the initial tangential velocity V_θ for ε=0 (circle symbols), ε=0·5 (inverted triangles) and ε=0·9 (squares). In agreement with previous studies[1–8] it was found that the role played by nozzle eccentricity is to delay vortex formation and even to inhibit it for the largest value of ε. Thus, for the largest eccentricity (ε=0·9) no vortex was observed for any of the considered values of V_θ A more detailed analysis of these experiments can be found elsewhere.[15]

To relate the above results with typical full scale molten steel drainage, it is possible to use the dimensional analysis proposed by Sankaranarayanan and Guthrie.[8] They conclude that the dimensionless critical height H_c/H_0 depends on only two hydrodynamics parameters: a Reynolds number defined as $Re=V_{out}H_0/\nu$ (V_{out} is the initial output velocity, ν is the kinetic fluid viscosity) and the vortex number defined as $K_v=V_\theta R/(V_{out}d_n/2)$. It is argued[6,8] that the extremely large Reynolds number values reached both in physical modelling and in actual casting practice make this parameter irrelevant in vortex formation. Thus, the vortex number becomes the key parameter to establish similarity criteria.

In Fig. 5 it is observed that for ε=0·9 no vortex formation occurs even for values of V_θ as large as 10 cm s^{-1} ($K_v \approx 3$). Therefore, for a ladle with a similar nozzle eccentricity, D=200 cm, H_0=300 cm and d_n=10 cm, an initial tangential velocity larger than 60 cm s^{-1} should be necessary for vortex sink to appear. Assuming that the filling process in actual practice excludes the possibility of having such large initial tangential velocities, it can be concluded that no vortex sink is present in typical full scale molten steel drainage.

Considering the above discussion, in the following section the numerical simulation of a full scale drainage process focused on the drain sink phenomenon is presented.



a numerical domain; *b* ladle dimensions

6 Oblong ladle with 2·5° floor inclination

Numerical results

Numerical simulations were carried out by the Computational Department of the Centre for Industrial Research, FUDETEC.

The drainage of the ladle was calculated with a finite element model of incompressible turbulent flow[16] programmed in the code FANTOM.[17] Isoparametric hexahedral elements were used, with linear interpolation for the velocity field and constant interpolation for the pressure. The incompressibility constraint was imposed by penalisation.[18] A pseudoconcentration technique was used to capture the steel surface.[19] These methods have already been employed with success to analyse the flow of steel in the continuous caster.[20,21]

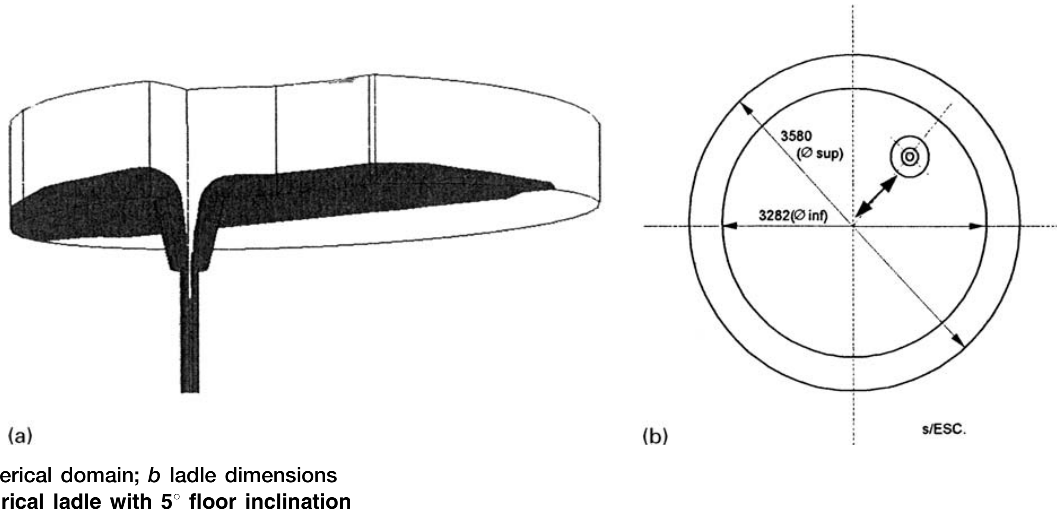
In this section, numerical results obtained with two geometrically different industrial ladles are presented.

First, consider the drainage of a ladle with an oblong cross-section and with floor inclination of 2·5°. The discharge cone has a height of 283 mm and the nozzle a diameter of d_n=7 cm. In Fig. 6*a*, part of the simulated domain shortly after eruption of the free surface in the nozzle is shown (in this case the slag layer was not simulated), with liquid steel (density 7·5 g cm^{-3}, viscosity 0·053 g cm^{-1} s^{-1}) represented by grey shading. The dimensions of the ladle cross-section are shown in Fig. 6*b*.

Then, consider a cylindrical ladle with a floor inclination of 5°, as represented in Fig. 7. The discharge cone has a height of 250 mm and a diameter of d_n=6 cm. In this case a slag layer (density 2·8 g cm^{-3}, viscosity 2 g cm^{-1} s^{-1}) was included in the model.

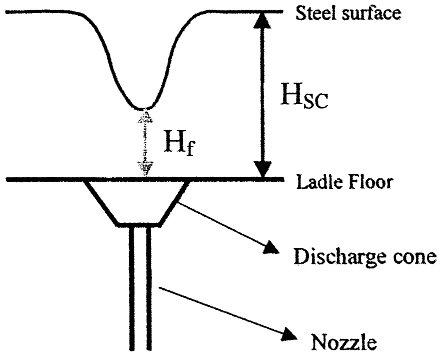
In both ladles the nozzle is located near the wall with an eccentricity $\varepsilon \approx 0{\cdot}8$. No tangential velocity was imposed as the initial condition since, as mentioned above, only drain sink formation is to be analysed. Wall functions were imposed as boundary conditions on the ladle walls and the velocity field was fixed at the nozzle exit according to actual teeming flowrates taken from plant reports.

Of interest is the evolution of two magnitudes: the 'funnel' height H_f and the 'steel column' height H_{sc}. The funnel height is the distance from the ladle floor to the steel surface just above the nozzle. The steel column height is the distance from the ladle floor to the steel surface in the proximity of the nozzle but in a place where the surface is flat (i.e. where the surface is not deformed due to the presence of the sink). These magnitudes are represented in the diagram of Fig. 8.



a numerical domain; *b* ladle dimensions

7 Cylindrical ladle with 5° floor inclination



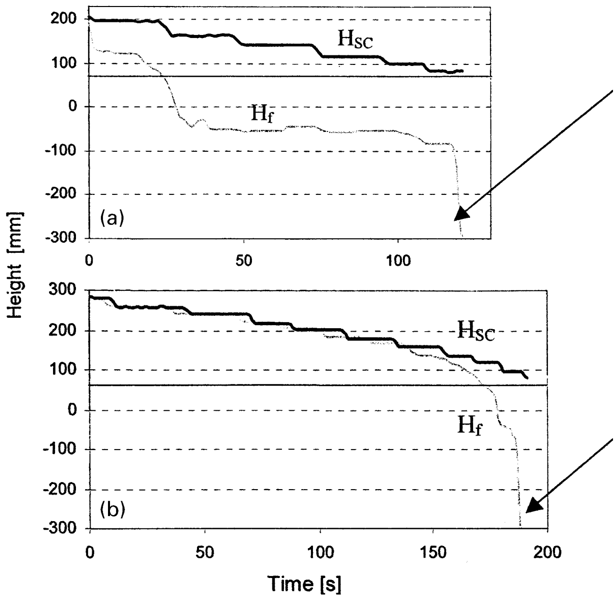
8 **Funnel height H_f (grey arrow) and steel column height H_{sc} (black arrow)**

Time evolutions of the funnel (grey line) and steel column (black line) heights are plotted in Fig. 9 for both analysed cases, for the last minutes of ladle teeming. The straight line in both Fig. 9*a* and *b* represents a height equal to the diameter of the nozzle d_n.

Since the funnel height is measured from the ladle floor, it becomes negative when the steel surface reaches the discharge cone. However, of interest is the eruption of the steel surface in the nozzle. For the first ladle, with the oblong cross-section, the eruption of the surface in the nozzle takes place when the grey curve reaches the value −283 mm (the discharge cone depth). For the ladle with the circular cross-section, surface eruption in the nozzle occurs when the grey curve reaches the value −250 mm. In spite of the different ladle and discharge cone geometries, in both cases eruption takes place when H_{sc} reaches a critical height $H_c \approx d_n$ (i.e. when the black curve approaches the straight line in the graphs).

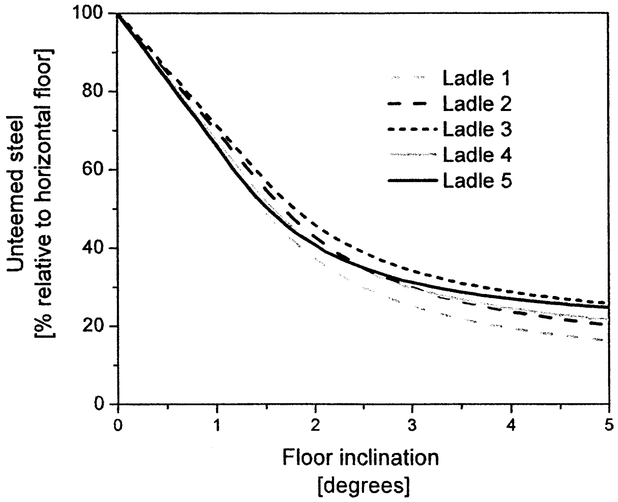
Analysis of results

Under general ladle teeming conditions in the plant, there is no preferred sense of rotation for the steel in the ladle, so it is reasonable to assume that there is no significant residual tangential velocity at the beginning of draining of the ladle. Besides, nozzles are extremely eccentric in industrial ladles. Experimental water modelling results indicate that under such conditions vortex formation is not expected to take place. The absence of a vortex during industrial ladle teeming is in agreement with the amount of steel usually downgraded in steel plants;[22] otherwise, the amount of wasted steel would be larger.



a oblong ladle; *b* cylindrical ladle

9 **Time evolution of funnel height H_f (grey curve) and steel column height H_{sc} (black curve): arrow indicates nozzle eruption**



ladle 1: 95 t, 2124 mm, 2525 mm; ladle 2: 195 t, oblong cross-section (Fig. 3); ladle 3: 96 t, 2373 mm, 2682 mm; ladle 4: 200 t, 3282 mm, 3580 mm; ladle 5: 164 t, 2943 mm, 3269 mm 3

10 **Steel left in ladle as function of floor inclination for ladles of given capacity, bottom diameter and top diameter: theoretical values obtained from geometrical considerations**

Once the absence of a vortex has been accepted, drain sink appears to be the mechanism that causes slag carryover under industrial conditions. In this context, the critical height (the height of steel remaining in the ladle when slag carryover starts) is approximately equal to the diameter of the exit nozzle. Once more this conclusion is not only taken from the literature but also observed in experimental and numerical simulations presented above.

As numerical results indicate, the critical height (in the neighbourhood of the nozzle) is not affected by floor inclination; then, the amount of steel that remains unteemed in the ladle can be strongly reduced by inclining the floor by a few degrees. From geometrical considerations it is possible to calculate the amount of steel left unteemed in a given ladle when the floor is inclined by α degrees in terms of the amount of steel left unteemed when there is no floor inclination ($\alpha=0$) This is shown in Fig. 10 for industrial ladles of various steel plants.

Figure 10 shows that the amount of wasted steel decreases drastically as the floor inclination increases from 0 to 2°. At this point, the amount of steel left in the ladle is ~40% of the steel left when there is no floor inclination. By increasing the inclination from 2 to 5° still important savings can be achieved, but the slope of the curves decreases. Finally, the curves show that no further improvement can be obtained with a floor inclination beyond 5°.

It must be noted that these results are valid as long as the floor remains inclined. Obviously, after several heats the ladle floor will lose its original shape, so steel savings will be reduced.

Conclusions

The ladle draining process has been analysed from both experimental and numerical points of view. Experimental analysis was carried out using a water model by analysing the conditions for which vortex formation is observed. Numerical analysis was conducted by modelling the turbulent flow inside different industrial ladles by the finite element method.

In consistency with results found in the literature (*see* for instance Refs. 1 and 7), experimental analysis shows that for highly eccentric nozzle location, no vortex is likely to take place during the draining process. Thus, under industrial conditions slag carryover occurs only due to drain sink formation.

Both experimental and numerical analyses show that drain sink takes place when the height of the column of steel in the ladle is approximately equal to the nozzle diameter. This result is in agreement with those reported by other authors[1,4,6] for a flat horizontal ladle floor.

Numerical results for ladles with eccentric nozzles and different cross-sections indicate that the critical height depends only on the nozzle diameter and does not depend on discharge cone geometry or floor inclination. As a consequence the amount of steel left in the ladle can be strongly reduced by inclining the ladle floor by between 2 and 5°.

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