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CFD MODELING OF ZINC VAPOUR FLOWS IN A CONTINUOUS STRIP COATING LINE

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ABSTRACT

In the continuous strip coating process a thin layer of zincalume (approx. 45% zinc, 55% aluminium) is applied to a steel strip by drawing it through a molten bath. The strip is preheated in a furnace before passing through a narrow opening into a chamber above the zincalume bath. This discharge chamber is extended below the bath surface by a 'snout' to seal the system from the atmosphere. An inert N_2/H_2 atmosphere in the furnace and discharge chamber prevents oxidation of the steel before it enters the bath. The motion of the strip generates a flow from the furnace into the discharge chamber with a corresponding backflow to the furnace. Zinc vapour from the bath surface is carried throughout the snout, discharge chamber and furnace, where it condenses causing maintenance and quality control problems. A CFD model of the process is developed to predict gas flow rates and zinc vapour concentrations throughout the system and examine the effectiveness of proposed changes to the process geometry designed to alleviate the problems of zinc vapour condensation.

NOMENCLATURE

k	roughness	m
k^+	dimensionless roughness	-
P_{Zn}	zinc vapour pressure	atmos
T	temperature	°C or K
v^*	friction velocity	ms^{-1}
ν	kinematic viscosity	m^2s^{-1}

INTRODUCTION

Applying a thin coating of zincalume to plate steel is a common means of protection against corrosion. The process is in principle a simple one, known as a continuous strip coating line. The steel strip, typically 0.9 to 1.8 metres wide, passes through a series of rollers at a constant speed of 1.5 to 2.5 metres per second on the way to the coating bath. The rollers accumulate sufficient lag time to allow the welding of the end of one strip to the beginning of the next, allowing the process to run continuously. The steel strip is cleaned before passing through a furnace in an inert atmosphere of 5% hydrogen in nitrogen. The furnace raises the temperature of the strip to around 500°C. The strip leaves the furnace through a narrow slot, entering the discharge chamber where it passes around a roller before plunging on an incline through the free surface of a bath of molten zincalume at 600°C. The inert atmosphere around the strip is maintained by extending the discharge chamber to below the surface of the zincalume bath to seal the system. The section which thrusts downwards to penetrate the bath surface is known affectionately as the *snout* (Figure 1). At the point of entry into the zincalume, chemical reactions between the steel and the melt occur, producing a layer of intermetallics a few microns thick which bonds the coating to the substrate. The strip passes around a submerged roller and is drawn vertically from the bath. Gas jet wipers at the exit of the bath blow away the excess zincalume leaving a thin, uniform coating.

Over a period of time it has been found that zinc vapour from the surface of the coating bath condenses leaving deposits of zinc-rich material on the walls of the snout, within the discharge chamber and in the furnace. This has adverse consequences for maintenance and downtime. In addition, quality control problems can arise when these deposits flake off and fall onto the free surface of the bath. This particulate matter is entrained onto the strip resulting in coating defects. The aim of the present work is to develop a CFD model to determine the gas phase flow and zinc vapour concentration throughout the snout and discharge chamber and to examine the effect of two proposed geometry changes.

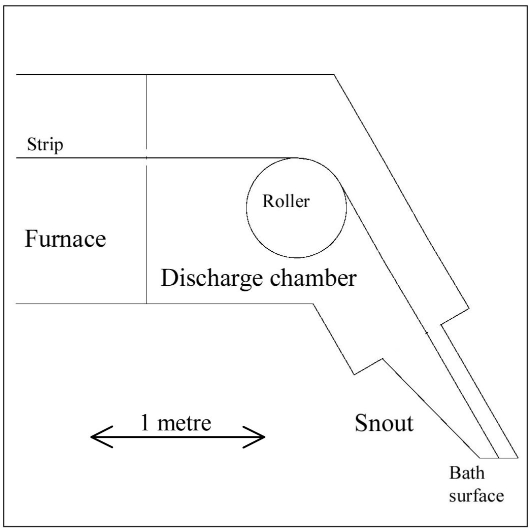

Figure 1 Schematic of furnace, discharge chamber and snout

MODEL DESCRIPTION AND RESULTS

Development of gas phase flow model

A 3-dimensional CFD model of the continuous strip coating process was developed using the CFX4.2 software. The grid consisted of 175,000 cells, and the default HYBRID differencing scheme was used. The flow was assumed to be steady state and turbulence was modeled via the *k*-ε model. Under the operating conditions the gas phase flow could be treated as incompressible and isothermal (500°C). The geometry of the discharge chamber in a typical coating line is shown in Figure 1. The model geometry includes a vertical symmetry plane along the centreline of the strip. The motion of the steel strip and the rotation of the roller drives the flow of gas within the discharge chamber. Although the entry of the strip into the bath will induce some motion of the free surface within the snout, this has no significant effect on the gas phase flow. Consequently the free surface is modeled as a stationary wall through which the strip passes. As the system is sealed at this end, the only way via which gas can enter or leave the system is through the narrow slot in the baffle separating the discharge chamber from the furnace, through which the strip passes (Figure 2).

The model begins with a short section of the furnace, sufficient to allow the establishment of the boundary layer being dragged by the strip before it passes through the slot in the baffle separating the furnace from the discharge chamber. The open end of the furnace was modeled as a constant pressure boundary as this results in an approximation to a fully developed boundary layer on the moving strip. Surface roughness of the strip has a significant effect on the usual logarithmic wall profile if (White, Chapter 6)

$$k^+ = \frac{v^* k}{\nu} > 4 \tag{1}$$

where v^* is the friction velocity, k the surface roughness and ν the kinematic viscosity. Under typical operating conditions $v^* \sim 1\ \mathrm{ms^{-1}}$, $k \sim 10^{-6}$ m and $\nu \sim 10^{-4}\ \mathrm{m^2s^{-1}}$. Thus $k^+ \sim 10^{-2}$, and the effects of strip roughness are negligible.

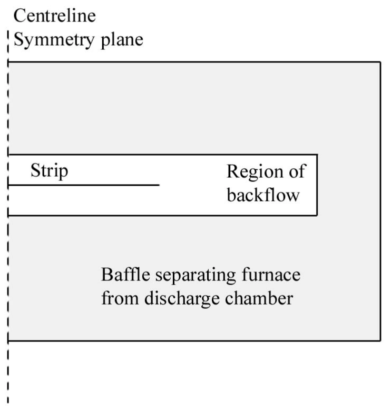

Figure 2 Schematic of baffle separating furnace from discharge chamber

The boundary layer developed on the strip in the furnace region is significantly thicker than the clearance of 35mm on either side as the strip passes through the slot in the baffle. Consequently a large part of the boundary layer developed in the furnace region is sheared off as the strip passes into the discharge chamber (Figure 3). The gas flow through the slot is directed entirely into the discharge chamber across the full width of the moving strip, however the slot extends well past the edge of the strip, and it is in this region that the backflow of gas from the discharge chamber to the furnace occurs (Figure 4). The velocity profiles across the slot were integrated to find the flow rate of gas into/out of the discharge chamber. Under typical conditions, running a 0.94m wide strip at a velocity of $2\mathrm{ms^{-1}}$, flows of 130 $\mathrm{m^3/hr}$ in either direction through the baffle were predicted.

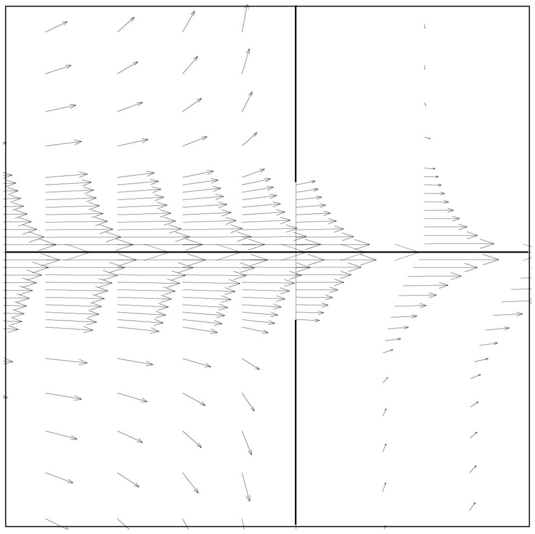

Figure 3 Shearing of the boundary layer on the strip as it passes through the baffle into the discharge chamber.

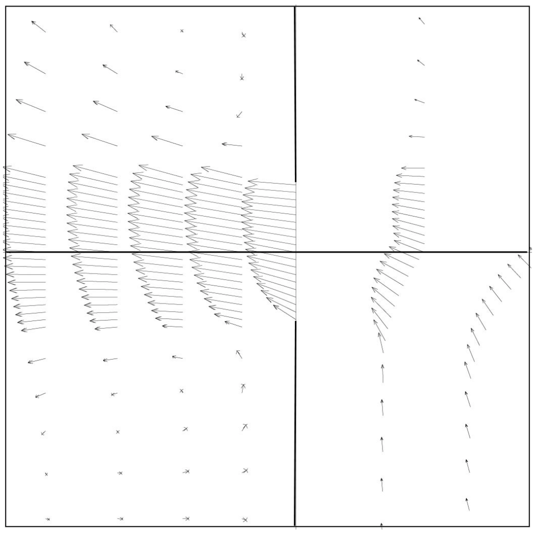

Figure 4 Backflow through the baffle from the discharge chamber to the furnace.

The other main area of interest in the flow pattern is the shedding of the boundary layer as the strip passes into the coating bath. Figure 5 shows the flow patterns within the snout. It can be seen that on the top side of the strip there is very little backflow. Near the strip centreline backflow along the top wall of the snout begins near the bath free surface, but is soon overcome by the strength of the boundary layer being drawn downwards by the strip, setting up a small recirculation zone. Instead the boundary layer shed from the top side of the strip as it penetrates the

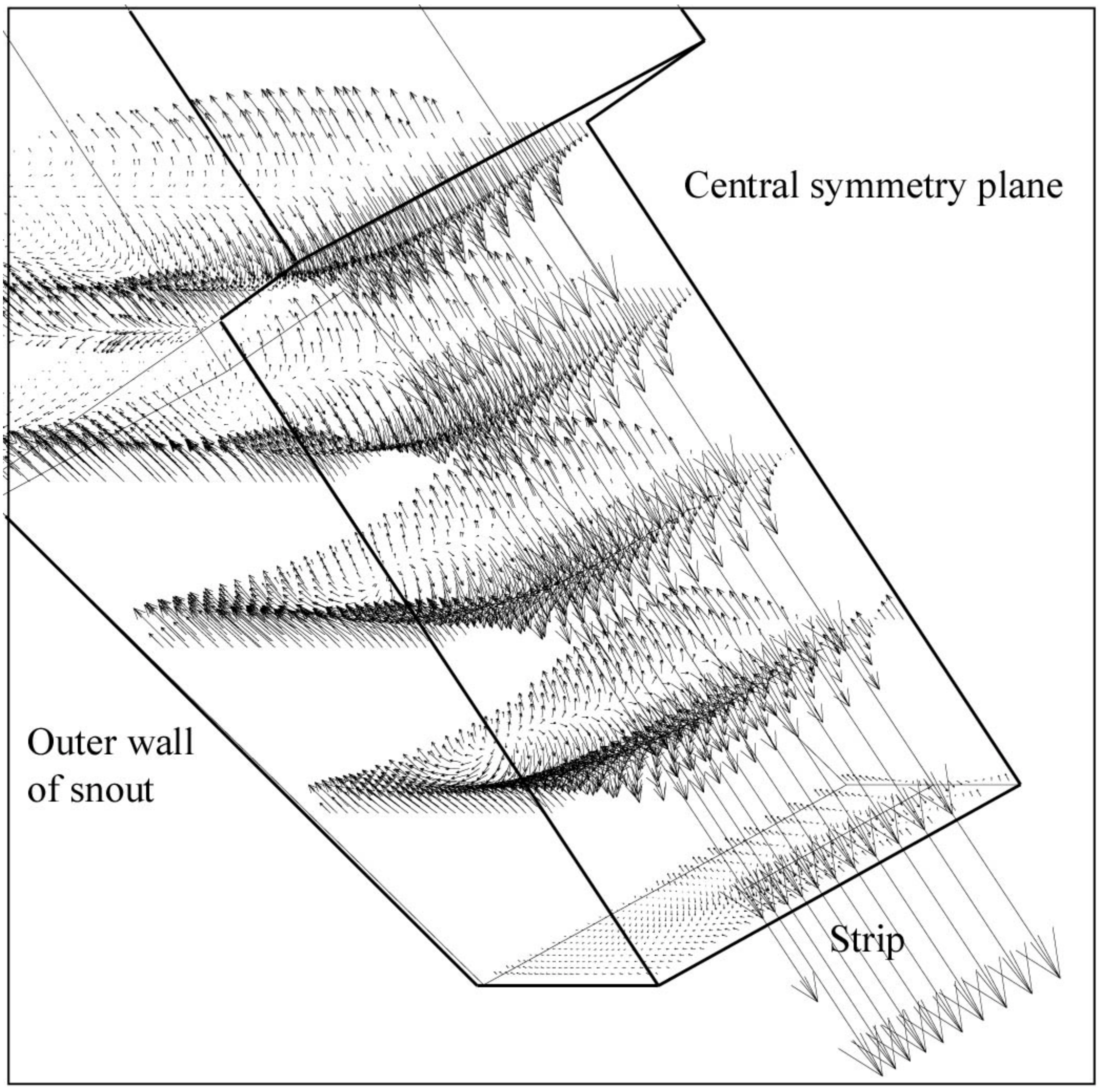

Figure 5 Flow patterns in snout

bath flows back up the outer walls of the snout. The boundary layer shed from the underside of the strip flows back up the bottom wall of the snout towards the centre of the strip.

The flow up the outer wall of the snout was to be anticipated as this path clearly offers less resistance to the flow. As demonstrated by the small recirculation zone near the strip centreline, the strength of the boundary layer is sufficient to offer resistance to backflow along the top surface of the snout across the width of the strip. However it might therefore have been expected that the boundary layer from the lower side of the strip might choose the same path. There are two reasons it does not. Firstly, the clearance between the top side of the strip and the snout wall is constant at 100mm along the length of the snout, comparable to the boundary layer thickness, whereas on the lower side the gap between the snout and the strip widens offering less resistance to backflow (Figure 1). Secondly the roller in the discharge chamber has a significant pumping effect, drawing gas up from the lower side of the snout and pushing it back towards the furnace (Figures 6 and 7).

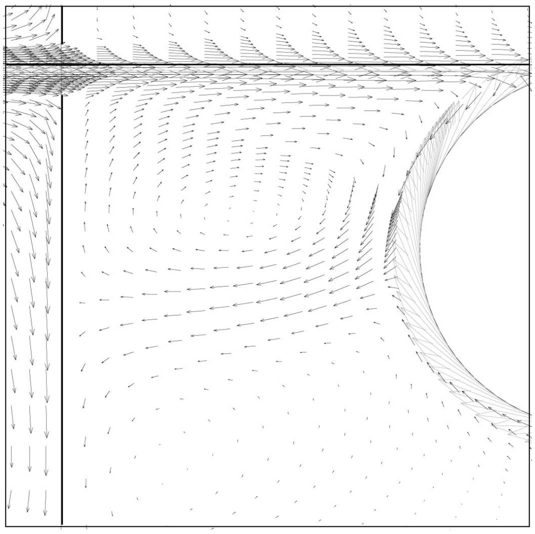

Figure 6 Backflow induced by roller, within strip width.

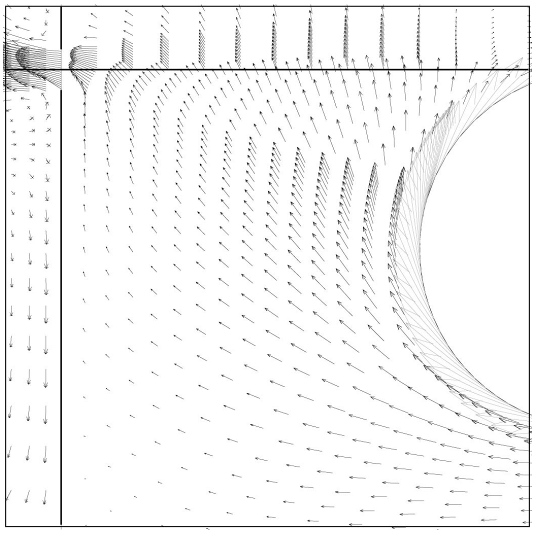

Figure 7 Backflow induced by roller, outside strip width

Zinc vapour concentration modeling

Zinc vapour from the free surface of the coating bath is carried throughout the snout and discharge chamber under the influence of convection and diffusion. The equilibrium vapour pressure P_{Zn} of zinc (atmospheres) above pure zinc is (Renshaw and Chen)

$$\ln(P_{Zn}) = \frac{-15644}{T} - 1.05\ln(T) - 0.29\times10^{-3}T + 21.05$$

while above zincalume this is reduced to

$$\ln(P_{Zn}) = \frac{-15644}{T} - 1.05\ln(T) - 0.29\times10^{-3}T + 20.27$$

where T is temperature (Kelvin). At the melt temperature of 600°C this gives $6.6\text{x}10^{-3}$ atmospheres (0.015 mass fraction), which is taken as the boundary condition for the zinc vapour concentration at the bath free surface.

The assumption of isothermal conditions in the gas phase made in the flow modeling is an idealisation which has no significant consequences for the flow patterns predicted in the system, but is potentially important in modeling zinc vapour concentrations. Near the bath free surface higher temperatures are to be expected in the gas phase and wall temperatures will also be elevated due to conduction from the melt. Higher up the cooling of the snout by natural convection will result in wall temperatures less than 500°C, and condensation may occur on these cooler surfaces. The assumption of isothermal conditions would seriously compromise the zinc vapour concentration modeling if the model predicted concentrations in excess of the equilibrium vapour pressure. At 500°C the equilibrium vapour pressure of zinc (above zinc) is $1.67\text{x}10^{-3}$ atmospheres (0.004 mass fraction). Ultimately the results of the model based on isothermal conditions only exceeded this figure in the region within about 5cm of the bath free surface (Figure 9), where in any case the temperature will exceed 500°C.

Condensation of zinc on cooler surfaces within the snout and discharge chamber was not incorporated into the model. The dependence of saturated zinc vapour concentration on temperature is a strong one (Figure 8, Eqn (2)), so any model incorporating condensation requires accurate temperature predictions. Details of the inside wall temperatures were not available, and it was felt that attempts to model these temperatures would necessarily involve too many assumptions to make the results credible.

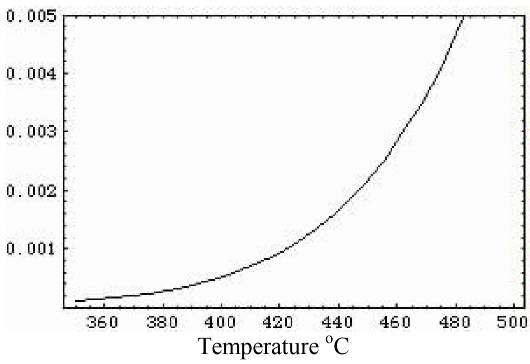

Figure 8 Saturated mass fraction of zinc vapour as a function of temperature

The mass fraction of zinc vapour in the gas stream flowing from the discharge chamber back to the furnace was of the order $5\text{x}10^{-4}$, which amounts to about 0.5 kg/day of zinc entering the furnace. The zinc vapour concentrations in the snout are displayed in Figure 9.

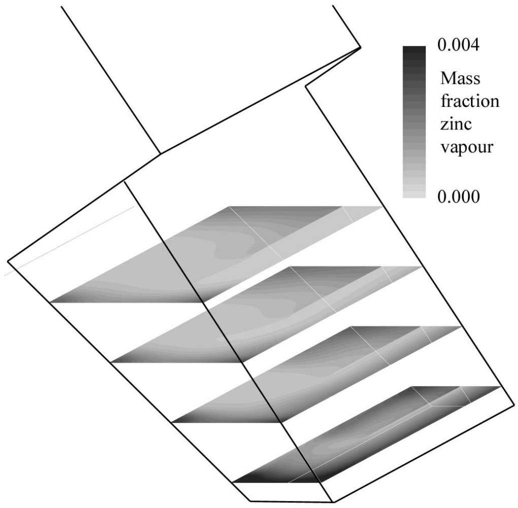

Figure 9 Mass fraction of zinc vapour in N_2/H_2 atmosphere within snout. (Planes shown are 5,20,35 and 50 cm above bath surface.)

It can be seen that although the boundary condition at the bath free surface set the mass fraction of zinc vapour as 0.015, within 5cm of the surface the concentration has fallen to a fraction of that figure. The regions of higher zinc concentration follow the two backflow routes identified above, corresponding to the boundary layers on the upper and lower sides of the strip. Zinc condensation is most likely to occur along these paths, although this is also dependent on the wall temperatures. When the zinc vapour saturation levels (Figure 8) are coupled with the zinc concentrations in the snout (Figure 9) the required wall temperature to eliminate condensation at any point on the snout wall can be inferred. Heating of the snout is one method which has been considered to eliminate condensation (Renshaw and Chen).

Strategies for alleviating zinc condensation

Two changes to the process geometry were proposed as possible strategies for reducing the problems caused by zinc condensation.

One proposal is to confine the zinc vapour to the snout region by an additional slotted baffle at the top of the snout. Modeling of this proposal showed that it reduced zinc vapour concentration in the discharge chamber by up to two orders of magnitude, making the backflow of zinc vapour to the furnace insignificant. However in the snout itself the zinc vapour concentrations increased considerably, signalling the likelihood of increased condensation rates in that area resulting in quality control problems (Figure 10).

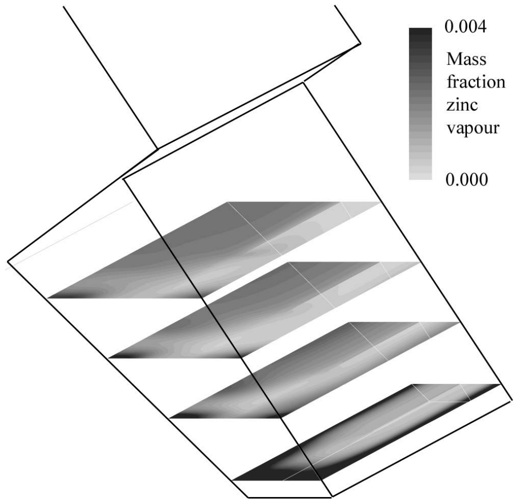

Figure 10 Mass fraction of zinc vapour in snout with baffle at snout entrance.

Rather than confine the gas to the snout region, another proposal was to withdraw the gas, rich with zinc vapour, from the snout. The zinc vapour could then be removed in a remote location and the gas returned to the system. This alternative is shown in Figure 11, where a duct to extract gas from the snout was included in the outer snout wall between 5 and 20 centimetres above the bath surface. Comparison with Figure 9 shows little reduction of the zinc concentration within the snout. However concentrations in the discharge chamber are halved as a consequence of the reduced backflow. The amount of zinc vapour escaping to the furnace is correspondingly reduced, to about 0.15 kg/day, both because the concentration is lower and the volumetric rate of backflow is also less. Nevertheless the failure of this approach to reduce zinc vapour concentrations significantly in the snout is disappointing. Two explanations are forthcoming. Firstly, the removal of zinc rich gas from near the bath surface has the effect of promoting additional evaporation of zinc rather than dramatically reducing the zinc vapour concentrations within the snout. Secondly, by placing the extraction duct in the outer wall of the snout, only the gas shed from the upper boundary layer on the plate is affected. The boundary layer on the lower side of the plate continues to flow back along the underside of the snout, carrying zinc vapour back towards the discharge chamber.

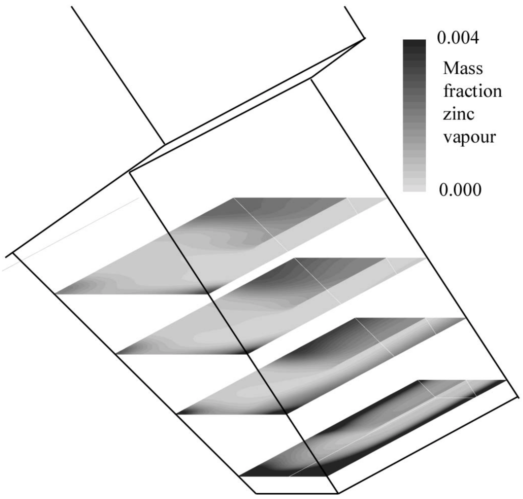

Figure 11 Mass fraction of zinc vapour in snout with extraction duct.

CONCLUSION

A CFD model of gas flows and zinc vapour concentrations in the snout and discharge chamber above a continuous strip coating line was developed using the CFX4.2 software package. It was found that in the existing system gas flows into and out of the discharge chamber of 130m^3/hr were to be expected, carrying away about 0.5kg/day of zinc vapour. This amount could be modestly reduced by the inclusion of an extraction duct in the snout, and almost completely eliminated by baffling at the snout entrance.

Gas flow patterns in the snout followed two distinct routes. The boundary layer carried by the top side of the strip flowed back along the outside wall of the snout, while that from the underside of the strip flowed back along the lower wall of the snout. Baffling of the snout entrance raised the zinc vapour concentrations within the snout significantly, increasing the likelihood of problems arising from zinc condensation. Extracting the gas from the outer wall of the snout as a means of reducing zinc vapour concentrations was not found to be effective, as it did not capture the flow from the underside of the strip, and promoted additional evaporation from the bath surface to replace the zinc vapour extracted.

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