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NUMERICAL MODELLING OF HEAT TRANSFER IN A TUBE FURNACE FOR STEEL WIRE ANNEALING

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ABSTRACT

In order to relieve stresses from cold drawing and to regain ductility, steel wires are annealed in furnaces under prolonged exposure to an appropriate temperature termed as ‘soaking’. This ensures the attainment of the required product quality. Literature suggests that the annealing processes are still determined by trial and error approach due to a lack of standards and also due to the proprietary nature of furnace designs. This paper investigates the heat transfer mechanism in a 12-metre long tube furnace filled with an inert gas and through which a cold-rolled steel wire travels at a specified speed. The length of the furnace is divided into three regions i.e. heating zone, soaking zone and cooling zone of which the heating and the cooling zones are given special attention.

The methodology involves the use of Computational Fluid Dynamics by coupling both solid (steel wire) and gaseous zones (Hydrogen or Nitrogen). Radiation has been incorporated via a suitable model and convection taken care of by considering laminar flow of gases. The results suggest that the time needed in the heating zone is influenced by the choices of the surrounding atmosphere, speeds of gas and of the wire. These factors have an impact on the wire drawing speed and eventually on the overall productivity. It is also implied that the proposed numerical method may be used to shorten the ‘soaking’ time and hence to reduce energy consumption. The work demonstrates the usefulness of CFD in understanding and optimisation of the transfer process as well as highlights the challenges associated with numerical results.

KEYWORDS: Wire annealing; Heat transfer in tube furnace

1. INTRODUCTION

To relieve stresses from cold drawing and to regain ductility, steel wires are annealed in furnaces at appropriate temperatures. The process of annealing is usually accomplished by two methods, either by allowing big coils of steel wires to ‘soak’ in a controlled furnace environment known as batch annealing or by continuously feeding the cold-rolled wire through tube furnaces at a controlled speed. Prolonged exposure at high temperature accelerates the stress relief and crystal alignment processes such that the final product regains the correct properties for further rolling or for delivery to the customer. In order to ensure a good surface quality, the environment inside the heated furnace is maintained by various non-oxidising gases such as hydrogen or nitrogen [3]. In the case of a tube furnace, which is the main concern in this work, the steel wires are fed through a fairly long heated tube maintained at a specified temperature as shown in Fig. 1. Typically there will be there will be three zones of wire inside the furnace as far as the wire temperature is concerned: the heating zone (increasing temperature), ‘soaking zone’ (constant temperature) and cooling zone (decreasing temperature). In order for the metal crystals to align and for the steel wire to regain the expected yield strength, the soaking zone should be of sufficient duration. When the wire comes out of the tube furnace, a small sample of the wire is checked for tensile strength and hardness. If the required strengths are not met, then the wires are passed through additional annealing operations making the process less efficient and more expensive. A typical wire drawing is completed in several steps of alternate cold drawing and annealing processes in a series and is very time consuming. Clearly, a faulty annealing disrupts the flow of material and means extra work to set new annealing parameters. The net effect means a loss of productivity. The process of tube furnace annealing has evolved essentially by trial and error and rigorous scientific literature on this type of furnace is very limited. On the other hand, batch annealing is suitable for very large production rate, and a considerable attention has been given to these processes and as such a rich volume of literature exists [6, 7]. To highlight the focus of the present work, few relevant issues that came out of the literature is briefly discussed in the next paragraph

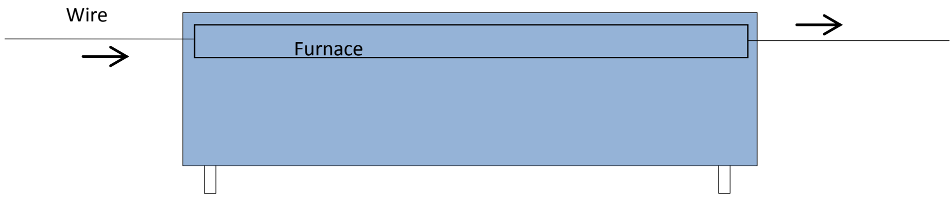


Fig. 1 Schematic of tube furnace annealing of steel wire

The process of annealing is dependent on the heat transfer mechanism from the furnace wall to the core of the wire by radiation and convection through the gases. In the case of batch annealing of steel wire coils, conduction is also very significant [6]. The fact that the wires are wound in layers, the heat transfer process is further complicated due to thermal contact resistance and air voids. Zuo et al [12] have reported work on the heat transfer for High Performance Hydrogen Bell type furnace. They have highlighted the importance of surface heat transfer coefficient and determined an ‘equivalent’ radial thermal conductivity similar to Zhang et al [11]. Useful data on heat transfer coefficient for H_2 and N_2 gases for steel and aluminium have also been reported in this work. The general findings from these and other papers such as Herring [3] suggest that the use of hydrogen is more efficient due to its higher thermal conductivity than nitrogen. However, hydrogen is more hazardous and hence the installations are likely to be more expensive. An important difference between batch annealing and tube furnace annealing is that the latter has a much higher gas flow rate. According to Herring [3], the number of gas changes for batch annealing is only

5, whereas it is about 10 times more for tube furnace annealing. This also highlights the importance of the fluid dynamics involved in the process.

From design considerations, the items of significance are the diameter of the tube, type of gaseous atmosphere, flow rate of gas used, speed of wire and temperature of the heating surface etc. Since the designs are essentially evolved by trial and error, the fundamental thermo-fluidic mechanism is not very well understood. For example, although the heat transfer is known to be largely by radiation, the relative contribution by radiation and convection are not unclear. Another important aspect is the temperature variation within the wire during the heating and cooling lengths. To ensure sufficient 'soaking' length (i.e., where the wire temperature is kept constant to ensure stress relief and re-crystallisation), the exact lengths need to be ascertained. Too short 'soaking' length may lead to incomplete annealing, whereas too long length means lower productivity. The rate of heating and cooling may also prove to be useful from metallurgical considerations. Additional aspect that needs to be considered is that the heating/cooling processes at the two ends are essentially transient. The low value of the thermal conductivity of steel may represent a time lag for the core temperature to reach that of the surface temperature. So, in reality the actual 'soaking zone time' is shortened further due to the above reasons. Detailed analysis of the heating process can provide sufficient information so that a well understood and scientifically sound decision can be made while optimising such processes.

In light of the previous discussion, the objective of this work has been set to investigate the thermo-fluidic transfer process with particular attention to the heating and cooling zones. The proven tool of Computational Fluid Dynamics which has shown great promise for similar situations [10] has been used. The work is also intended to highlight the challenges associated with the numerical prediction of such situations so that care may be taken to interpret numerical data with confidence and to give direction to experimental data acquisition.

2. METHODOLOGY

Calculations were carried out using the commercial CFD software FLUENT available within ANSYS 13.0 [1]. The methodology involves domain specification, suitable grid generation, boundary condition specification, flow solution and post-processing. The steady state governing Navier-Stokes equations along with a scalar energy equation were solved simultaneously until a converged solution was obtained. A systematic grid refinement was followed with non-uniform grid distribution in areas of large gradients to ensure faster convergence but better accuracy. After several trial runs, grid independent results were obtained. Higher order differencing schemes were used for all equations [8]. A number of simplifications were made regarding boundary conditions and the important points are mentioned below. To highlight the transient nature of heat flow within the wire, some speculative calculations based on Heisler charts [4] were attempted and shown later in the paper.

2.1 Domain Specification

The wire being quite long will have some amount of sag. However, evidence from industry suggests that the wire does not touch the heating surface of the tube furnace. Given that the inside pipe diameter is only 42 mm against its length of 12 m, suggests that the angular deviation from the axis is very small (maximum of 0.003 deg) and hence the assumption of axisymmetric geometry has been considered. Also, as will be shown later in the results, the lengths of the heating and cooling zones where the temperatures are varying most, are fractions of the total length and hence the deviation from axisymmetry is even less. The soaking zone represents a constant and stable section where the axial gradients are negligible and is a further vindication of concentrating on the 2D domain.

2.2 Boundary Conditions

For the sake of this analysis, the boundary conditions are kept simple but realistic. The tube wall temperature is fixed and the speed of steel wire is specified. The inlet and exit boundary conditions for the fluid and solid zones (i.e., steel wire) are opposite to each (Fig. 2) and are specified below.

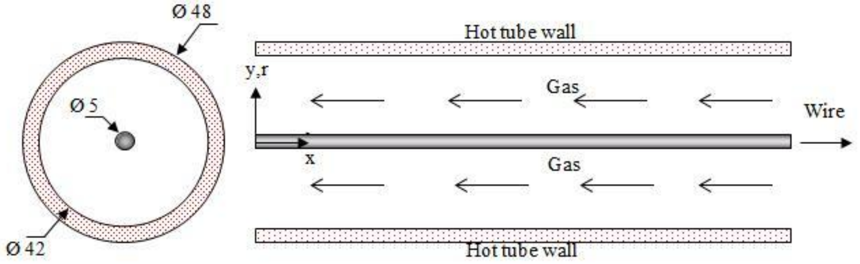


Fig. 2 Schematic of the domain, coordinates and directions of flow (all dimensions are in mm)

<u>Fluid zone: Gas</u>

Inlet: Temperature is 293 K and velocity is fixed according to the case (10 m/min and 20 m/min)
Outlet: Zero gradient condition specified for all variables

<u>Solid zone: Steel wire</u>

Temperature fixed at 293 K at both inlet and exit. Speed of steel wire is specified according to the particular case (e.g., 1 m/min to 20 m/min)

These boundary conditions were assumed due to lack of experimental data.

2.3 Specification of Property

Since the gas Reynolds numbers of the flows are very small (about 20 for Hydrogen and 100 for Nitrogen based on mean properties and diameter of the tube furnace), the flow is considered to be laminar. The radiation heat transfer has been modelled by the Surface to Surface [1] radiation model due to geometrical simplicity. The gases are not considered as participating medium. The surface of the wire is considered to be shiny and hence the emissivity was taken to be $\varepsilon = 0.066$. In the absence of specific information, the emissivity of the inside surface of the tube was taken to be $\varepsilon = 0.2$ which is similar to rough mild steel data.

Temperature dependent gas properties [2] were specified using piecewise linear profile for property variation for both nitrogen and hydrogen. For gas mixtures, piecewise linear profiles have been used by linear interpolation based on gas concentration.

3. RESULTS AND DISCUSSION

Computations were carried out for the whole length of the tube. The overall flow field is fairly simple where the velocity distribution of the gas attains a fully developed laminar profile along the axisymmetric slice. A typical temperature contour along the length of the tube is shown in Fig. 3.

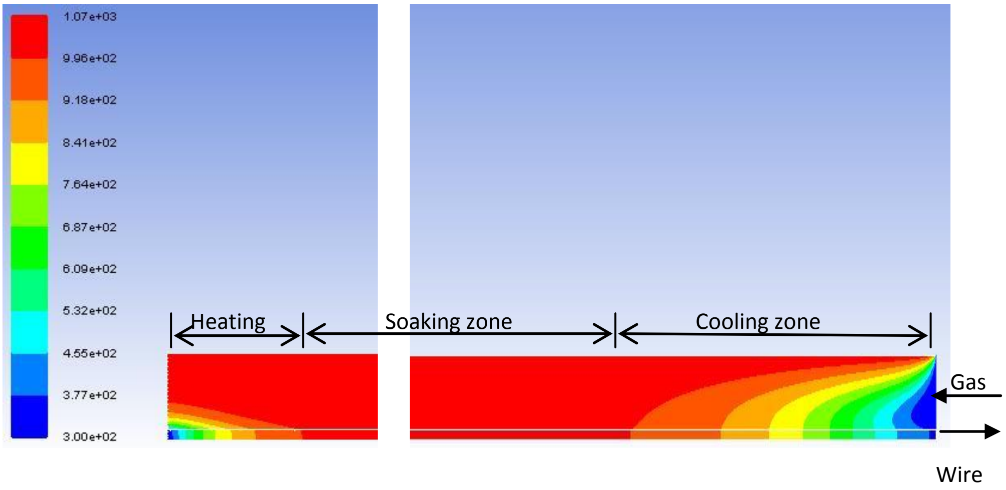
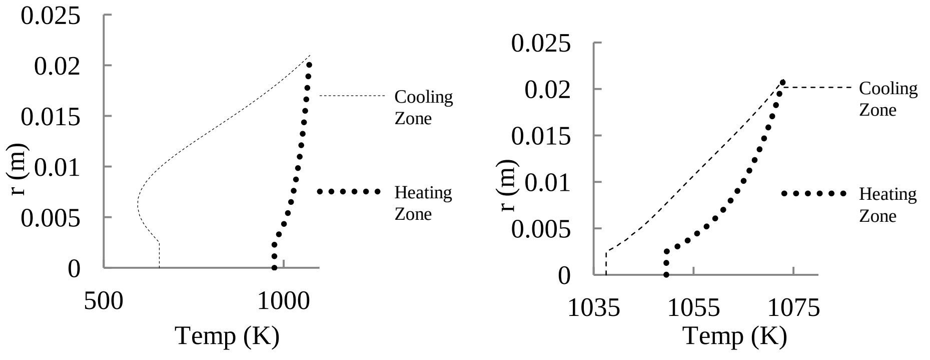


Fig. 3 Temperature distribution (N_2, V_{gas} = 10 m/min; V_{wire} = 1 m/min)

It can be seen that heating zone is much shorter than the cooling zone length. This is due to the counter flow arrangement of gas and wire motion (Fig. 2). The assumption of steady state solution can be seen from the temperature contours inside the steel wire. The detailed variations of temperature across the gas field are shown in Figs. 4a-b for the cooling and heating zones for two different gases.

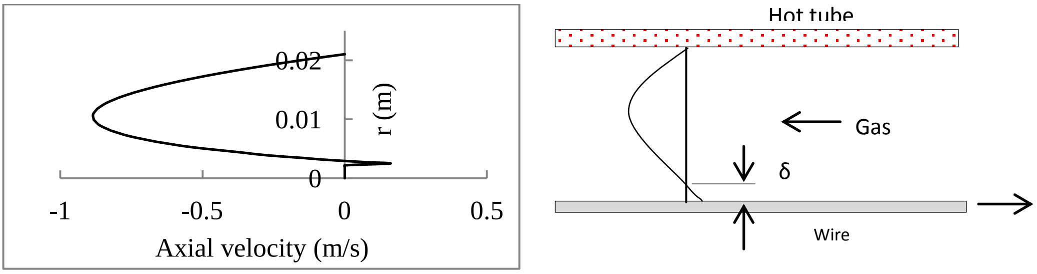


(a) N_2 (b) H_2

Fig. 4a-b. Radial temperature distribution within the gases

The temperature profiles for both gases highlight the effect of convection in these two zones and clearly demonstrate how heat is transferred to or taken out of the wire material. As already mentioned in the literature, one very distinctive difference is the higher velocities of the gases compared with batch annealing and hence the fluid dynamic mechanism needs further scrutiny. The above profiles could also act as validation data locations for experiments.

In line with this, the velocity profile in the soaking region is plotted in Fig. 5a. As expected a smooth parabolic profile representing fully developed laminar flow, can be seen with a fairly high maximum velocity due to rise in temperature in the furnace. An interesting feature can be seen near the r = 0.0025 m, (which represents the surface of the steel wire) where a small amount of fluid can be seen to be flowing in the opposite direction i.e., along the direction of wire.



(a) Actual profile

(b) Exaggerated view

Fig. 5 Velocity profile on the wire surface (N_2)

The adjacent sketch Fig. 5b shows this region on a highly exaggerated scale. Physically, this means that a ‘sheath’ of gas around the wire surface is moving with the same speed as that of the wire due to no-slip boundary condition [8] and hence the existence of a small (near) stagnating layer of fluid of thickness δ. This layer of fluid around the wire is found to vary significantly with the gaseous environment and is likely to be related to the viscosity difference (δ_{N2} = 0.9 mm ; $\mu_{N2} = 1.66 \times 10^{-5}$; ($\delta_{H2}$ = 0.3 mm ; $\mu_{H2} = 0.84 \times 10^{-5}$;). The heat transfer through this layer is likely to be dominated by conduction through the gas and supports the fact that H_2 is a superior medium. However, further detailed analysis has to be carried out by reference to the thermal and hydrodynamic boundary layers to understand the influence, in particular, in the heating and cooling zones.

3.1 Effect of gas mixture

In addition to pure H_2 and pure N_2, computations have been carried out for gas mixtures of various proportions. Both the heating and cooling length data were extracted and analysed. For the sake of precise definition, heating and cooling lengths are defined as the length where the temperature of the steel wire reaches within 2 K of that in the soaking zone. While the lengths of the heating zone were rather small (about 14-18 cm) for both gases, the magnitude and variations of cooling lengths are markedly dependent on gas mixture as shown in Fig. 6.

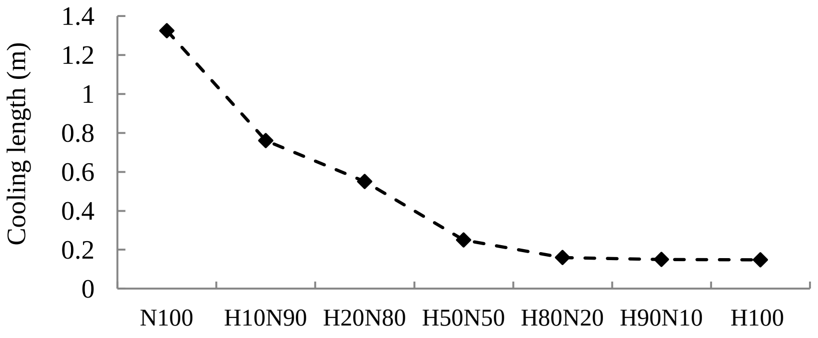


Fig. 6 Length of cooling zone for gas mixture (H10N90: H_2 10% and N_2 90%)

The above curve demonstrates a monotonic nature with higher H_2 concentration and the reason may be rooted to higher values of Cp (10 times more than N_2). This may be interpreted from the viewpoint of heat transfer that a diluted H2 gas mixture may still provide the same environment given that the non-oxidising characteristics of the atmosphere is not compromised. Due to the 'imposed' boundary condition of fixed temperature at the outlet plane for the solid zone, the steel wire must lose enough heat to the cooler gases entering through this end. Since this is a rather artificial boundary condition, the exact numerical values of the cooling lengths must be interpreted with caution. In reality, the cooling rate will be a lot slower due to the fact that as the wire comes out of the furnace it will be carrying some heat with it and will continue to be cooled by natural convection. It is not exactly known what effect it might have on the cooling length and this issue is a future extension to the project.

3.2 Effect of gas and wire speed and wall temperature on cooling length

Various combinations of gas and wire velocity have been specified and the results analysed for all combinations. H_2 gas did not show any significant effect due to gas velocity change from 10 to 20 m/min and wire velocity change from 1 to 10 m/min. However, significant effect on the cooling length and 'rate of cooling' has been observed for N_2 gas as shown in Fig. 7.

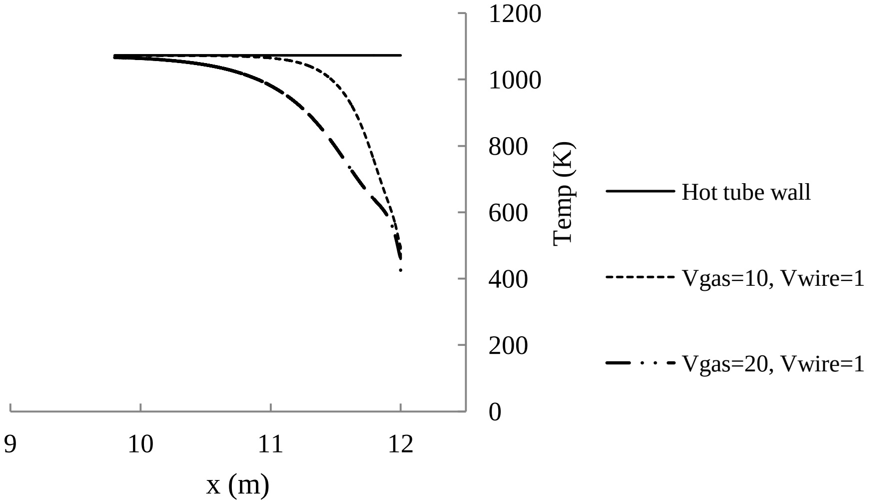


Fig. 7 Effect of gas velocity on cooling rate

The cooling length was found to increase from 1.1 m to 1.8 m, an increase of 64%. This is possibly due to the fact that the faster moving fluid needs more time to extract heat from the wire and hence needs to readjust to the cooling process much earlier. Such information may be significant in optimisation of the various steps in the wire drawing process.

Investigation has also been carried out by varying the wall temperature of the tube and the effect has been found to be negligible. Essentially, a 20 K rise in tube furnace temperature was found to increase the wire temperature by the same amount. The effects on the cooling and heating lengths were also found to be insensitive for such small temperature increases.

3.3 Transient heat conduction in the wire

Since conduction in a homogeneous metal follows the analytical equations, some typical curves were generated using the transient conduction equations available in the form of Heisler charts and related equations [4]. To appreciate the effect of the transient heating process, the steel wire has been considered to be an infinite cylinder exposed suddenly in a radiation-convection environment and the temperature variation with time at the core of the wire are shown in Fig. 8 for various values of surface heat transfer coefficient ‘h’. These ‘h’ values may be interpreted as a combination of convection and radiation heat transfer coefficient. The convection components of these ‘h’ values are high where temperatures of the wire are low, whereas radiation component would be dominating near the soaking region.

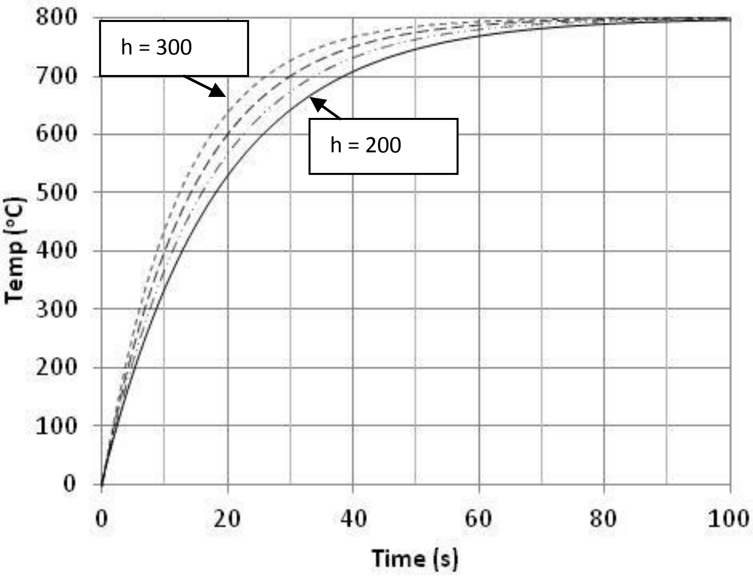


Fig. 8 Typical transient conduction curves for various h values

The net effect of the transient conduction within the wire is largely a shortening of the ‘soaking zone’ due to extension of the heating and cooling zones in the core region. However, the exact amounts can only be determined by doing a coupled analysis with CFD.

4. CONCLUSIONS AND FUTURE WORK

The most important outcome of this work is that the CFD tools can be used to do parametric analyses of the thermo-fluidic transfer mechanism within a tube furnace. Such analysis may be very expensive to carry out using experimental methods as opposed to numerical approaches.

The lengths of the cooling and heating zones have been identified for the chosen boundary conditions. The trends observed for various mixtures of H_2 and N_2 may be useful to the practitioners to make informed decisions.

The existence of a stagnating gas sheath around the circumference of steel wire needs a thorough scrutiny and this may be particularly significant in the choice of ‘h’ values required for transient heat transfer calculations.

The boundary conditions need further attention and work is currently underway to investigate this.

Finally, the work highlights the importance of reliable experimental data to be gathered and highlights the locations where instrumentation should be placed for data collection. With a reliable data validation, the CFD results may be coupled with re-crystalisation [5, 9] models to make it a complete tool.

5. Acknowledgements

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