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Flow control and optimization

In Continuous Furnaces

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Air infiltration during start-up and normal operation of continuous furnaces is a major problem experienced by the annealing and brazing industries. The infiltration of air causes oxidation, resulting in parts with unacceptable surface appearance and properties. Furnace operators try to prevent air infiltration by manipulating the atmosphere flow rate and location, and changing the number and location of inlet ports. However, because they often make adjustments without truly understanding furnace flow dynamics, this trial-and-error approach can be frustrating, time consuming, and expensive.

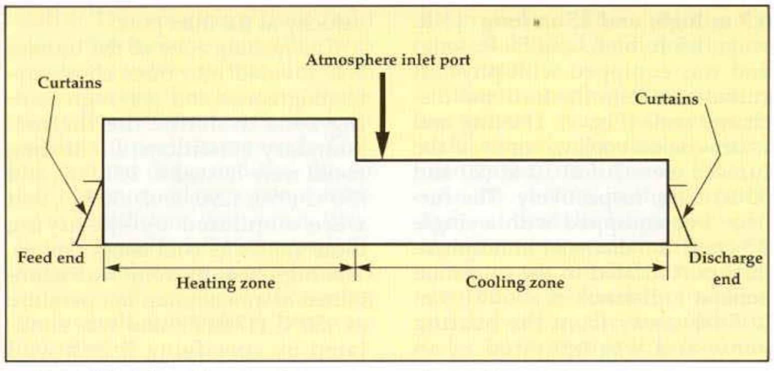

Fig. 1 Simplified schematic of a two-zone continuous furnace.

To help operators make the correct adjustment the first time, Air Products has developed a computer simulation package that is capable of simulating flow and temperature fields during start-up or normal operation of continuous annealing and brazing furnaces. This paper describes how the package can be used to adjust atmosphere turnover and location of atmosphere introduction points to optimize and balance flow while starting up a new furnace.

Furnace design

Continuous furnaces are generally operated in the presence of an

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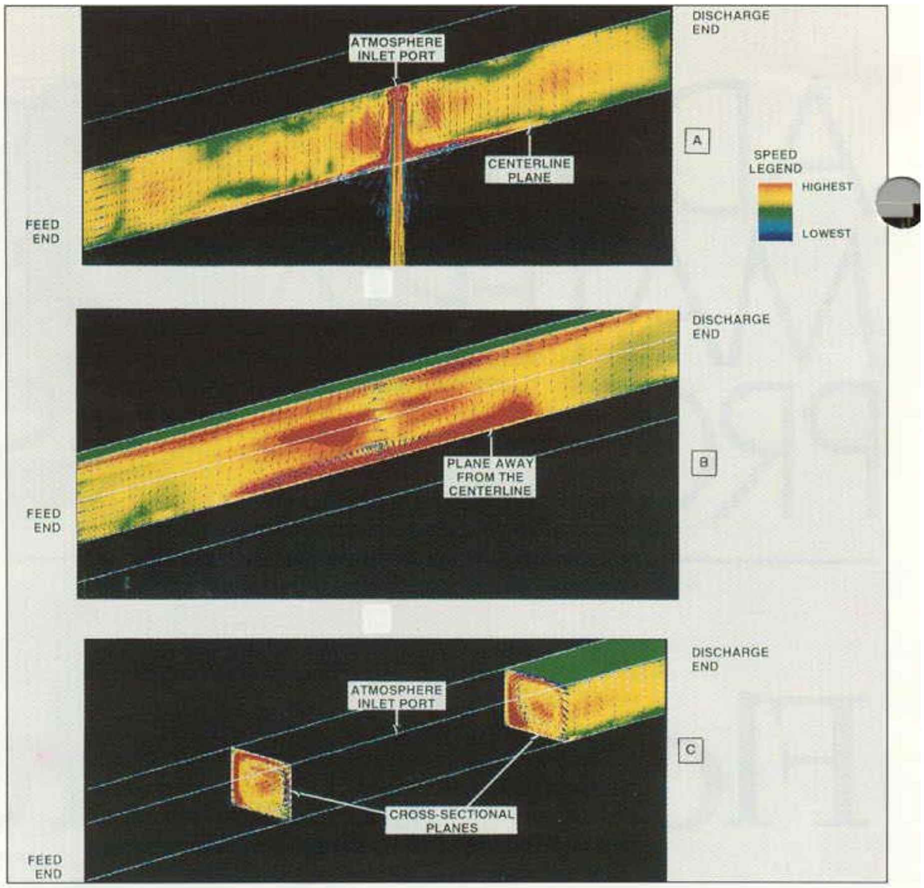

Fig. 2. Velocity vectors (showing both actual direction and magnitude) and speed contours along (a) furnace centerline plane, (b) a plane away from the centerline, and (c) cross-sectional planes on either side of the inlet port.

atmosphere that provides the desired reducing, oxidizing, or carbon potential. It also prevents air infiltration and concomitant oxidation of components by maintaining positive pressure. The atmosphere is normally introduced through an inlet port in the transition zone located between the heating and cooling zones.

Industry standards for selecting the correct atmosphere flow for startup and operation have been difficult to establish because the shapes, sizes, and functions of continuous furnaces vary considerably. Therefore, operators typically select the atmosphere flow rate based on prior experience with furnaces of similar design and size. This experience does not always provide accurate results: Improper selection of the atmosphere flow is the principal cause of air infiltration during start-up of new continuous furnaces. Furthermore, improper balance of the atmosphere flow is the principal cause of air infiltration in existing furnaces. In either case, operators usually solve the air infiltration problem by trial and error.

To demonstrate how the simulation program can solve the problem more efficiently, a two-zone continuous furnace operated at about 950°C (1740°F) was selected for simulation. It was 1 m wide, 0.5 m high, and 15 m long (3 ft. wide, 1.5 ft. high, and 50 ft. long) and was equipped with physical curtains on both the feed and discharge ends (Fig. 1). Heating and water-cooled cooling zones of the furnace were 7 and 10 m (20 and 30 ft) long, respectively. The furnace was equipped with a single 2.5 cm (1 in.) diameter atmosphere inlet port located in the transition zone at a distance of about 0.8 m (2.5 ft). away from the heating zone, and was operated in an atmosphere containing 90% nitrogen and 10% hydrogen.

Simulation setup

A computational fluid dynamics software package was used to define the model and to simulate flow and temperature fields. Furnace dimensions were selected to construct the model geometry and an optimal finite element mesh. A no-slip velocity condition was imposed at all wall boundaries in order to accurately simulate flow and temperature fields. The atmosphere turnover was defined by specifying the fluid velocity at the inlet port.

The heating zone of the furnace was divided into three short preheating zones and one high heating zone to define the thermal boundary conditions. Preheating zones were heated to 200, 700, and 850°C (390, 1290, and 1560°F), and were simulated by specifying these values as wall temperatures. The high heating zone was maintained at a maximum temperature of 950°C (1740°F), and was simulated by specifying it as a wall temperature.

Physical curtains at the feed and discharge ends were simulated by restricting the openings to about 50%. The density, viscosity, thermal conductivity, and heat capacity of a 90% nitrogen and 10% hydrogen mixture were calculated from properties of pure nitrogen and hydrogen gases under normal operating conditions. Finally, since the furnace geometry is symmetric with respect to the centerline, only one-half of it was modeled to save computational time.

Simulation results

As a starting point, the temperature and flow fields in the furnace were simulated using standard operating conditions and an initial atmosphere turnover of about 10/hr. The atmosphere turnover was calculated by dividing the total atmosphere flow rate by the total volume of the furnace. An initial turnover value of 10/hr was selected because it is typically selected by operators to start up a continuous furnace with similar dimensions. The atmosphere was introduced into the furnace through a single inlet port located in the transition zone and along the centerline of the furnace.

Thermal and flow fields are strongly coupled because the atmosphere flow is driven by "jetting motion" at the inlet por and buoyancy forces resulting from atmosphere temperature variations (or density variations).

Therefore, the flow and temperature fields were simulated by solving coupled momentum and energy equations.

Simulation of the temperature field along the furnace centerline revealed that the highest atmosphere temperatures were in the heating zone and the lowest temperatures were in the cooling zone. It also revealed rapid heating of the atmosphere as it entered through the inlet port and traveled toward the heating zone. However, simulation of the temperature field did not provide any information about infiltration of air.

Simulation of the flow field along the furnace centerline revealed a complex three-dimensional flow, characterized by a series of recirculation cells extending across the length of the furnace. Recirculation cells in the vicinity of the inlet port can be more clearly visualized by the velocity vectors in streamwise planes located at the centerline (symmetry plane) and slightly away from it, as illustrated in Fig. 2a and b. The full three-dimensional nature of these recirculation cells can be seen by the velocity vectors in the cross-sectional planes on either side of the inlet port (Fig. 2c). Flow fields along and slightly away from the centerline revealed a net movement of atmosphere flow from the inlet port toward the discharge end.

Close-up views of the velocity vector plots in planes of the feed- and discharge-end openings (Fig. 3a and b) clearly indicated strong atmosphere outflow through the discharge end and signs of ambient air infiltration through the feed end. This information suggested that the atmosphere flow rate or turnover selected to start up the furnace could not prevent air infiltration at the feed end of the furnace.

Optimized atmosphere flow

Air infiltration observed with the initial atmosphere turnover of 10/hr could be related either to insufficient atmosphere flow, or to flow disturbance caused by the introduction of atmosphere through a single port. The problem caused by insufficient atmosphere flow can be resolved by increasing the atmosphere flow rate or turnover. On the other hand, problems related to flow disturbance can be resolved by reducing the atmosphere flow rate or turnover.

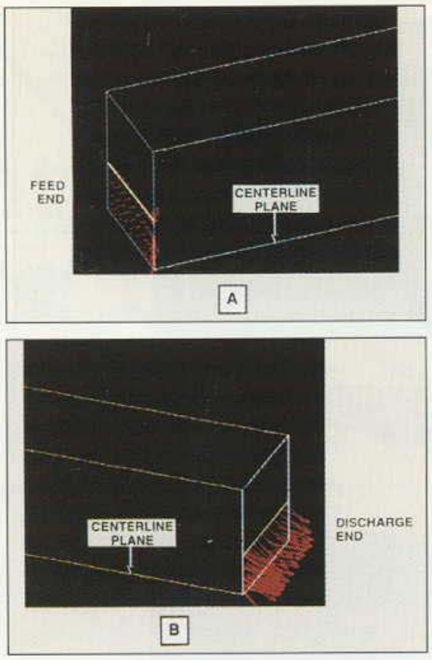

Fig. 3. Velocity vectors in planes of the (a) feed and (b) discharge-end openings.

To study air infiltration possibly caused by insufficient atmosphere flow, the flow field in the furnace was simulated again, this time with an atmosphere turnover that was twice the value used initially. The resulting flow field along the furnace centerline was similar in nature to that shown in Fig.3, except that flow recirculation, flow disturbance, and air infiltration all increased. This information suggested that the air infiltration problem was not related to insufficient atmosphere flow. It also suggested that the air infiltration problem in general cannot be resolved simply by increasing the overall atmosphere flow rate or turnover.

To study the effects of decreasing turnover, the next simulation reduced the atmosphere turnover by a factor of two relative to the initial value. Once again, the flow field along and slightly away from the furnace centerline (Fig. 4a and b) revealed a complex, three-dimensional flow characterized by a series of recirculation cells extending across the length of the furnace. However, the relative intensity of the flow recirculation and disturbance was decreased considerably (compare Fig. 2 and 4). The primary atmosphere flow was generally away from the inlet port and toward the feed and discharge openings, indicating that the atmosphere flow rate or turnover was sufficient to maintain a favorable pressure gradient in both the feed and discharge directions.

The velocity vector plots in the planes of the feed- and discharge-end openings very clearly indicated strong outflow of atmosphere in these regions. Additionally, there were no signs of any air infiltration, either from the feed or discharge-end openings. This information suggested that air infiltration during start-up of the furnace modeled here was caused not by the selection of *insufficient* atmosphere flow, but by the strong flow disturbance and secondary flows created by *excessive* atmosphere flow.

From an economical standpoint, it is beneficial to operate a furnace utilizing the lowest possible flow rate or atmosphere turnover. However, a minimum critical value of atmosphere flow rate or turnover must exist, below which favorable streamwise pressure gradients cannot be maintained and air infiltration cannot be prevented. This critical value was established by simulating the flow field.

The atmosphere flow rate or turnover was successively reduced in the simulation until air infiltrated the furnace. Plots of velocity vectors in the planes of the feed- and discharge-end openings for a furnace simulation with a turnover of 2.5/hr clearly showed no infiltration of ambient air. However, the magnitude of velocity vectors in the feed-end opening was not large enough to recommend the use of an atmosphere turnover of 2.5/hr. Furthermore, plots of velocity vectors in the planes of the feed- and discharge-end openings for a turnover of 1.25/hr clearly showed infiltration of ambient air at the feed-end opening. Based on these results, the continuous furnace simulated here requires an atmosphere turnover value sub-

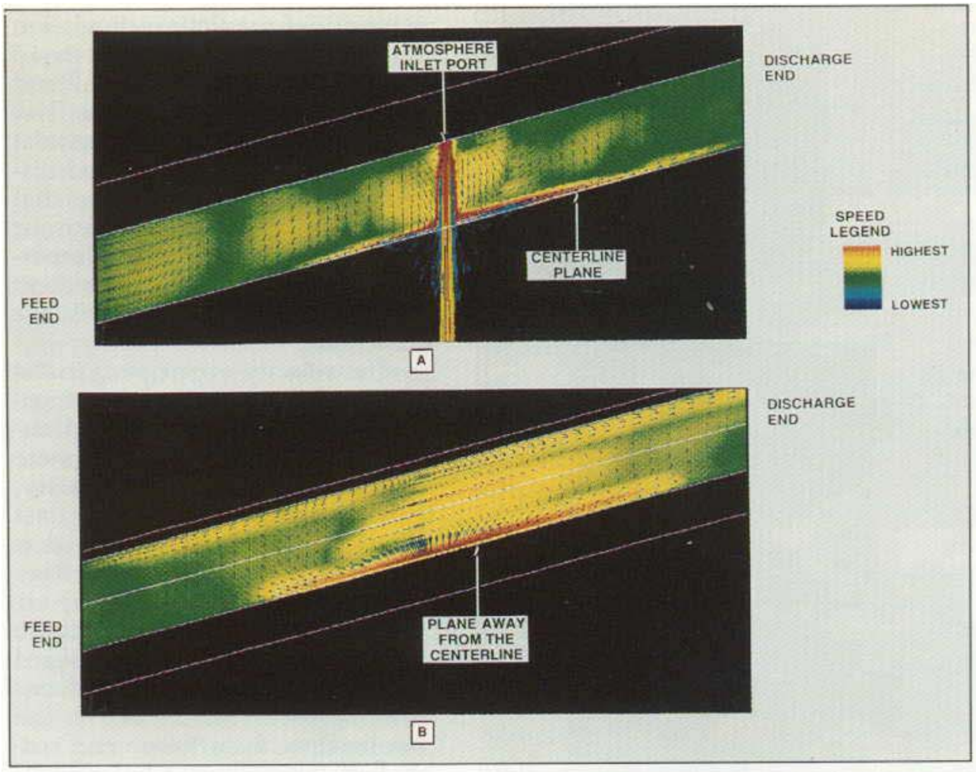

Fig. 4. Velocity vectors (showing both actual direction and magnitude) and speed contours along (a) furnace centerline plane and (b) a plane away from the centerline.

stantially above 2.5/hr to start up without ambient air infiltration.

Atmosphere introduction

The simulation of flow fields in the current furnace has clearly demonstrated that air infiltration at the feed-end opening can be prevented by either reducing the flow disturbance or decreasing the atmosphere flow rate. Because air infiltrated at the feed-end opening as a result of flow disturbance and secondary flows, we concluded that introducing atmosphere in the vicinity of the feed-end opening would wash out these eddies and prevent air infiltration. We also inferred that introducing atmosphere close to the feed-end opening would increase the magnitude of outflow at this opening, and therefore allow the use of a much lower atmosphere flow-rate or turnover in this furnace without air infiltration.

To test these conclusions, a turnover of 5/hr with an additional atmosphere inlet port located 0.75 m (2.5 ft) from the feed opening was simulated. Approximately 20% of the total atmosphere flow was diverted from the main inlet port located in the transition zone, and introduced through this new inlet port. Computed results showed a stronger outflow at the feed opening with the additional inlet port. These results suggest that the overall atmosphere flow rate or turnover could be reduced by using multiple atmosphere-inlet ports.

To confirm the positive benefits of using multiple inlet ports, a turnover of 2.5/hr with an additional atmosphere inlet port located 0.75 m (2.5 ft) from the feed-end opening was simulated. Once again, approximately 20% of the total atmosphere flow was introduced through this new inlet port, while maintaining the same overall atmosphere flow rate or turnover value. Results of this simulation showed a considerably stronger outflow of atmosphere at the feed opening than that noted with one inlet port, confirming the benefits of using multiple atmosphere inlet ports for this furnace. ■

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