# Vaporization Rates for Rolling Oil Using Computer Simulation Improves Safety in Coil/Foil Annealing

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## *Abstract*

The intent of this paper is to demonstrate the application of modern computer simulation methods to a typical furnace process. Heat treatment processes for metal products often involve various furnace operations. These processes are usually established with years of experimentation. Adjusting and improving the processes can require long-term experimental plans with difficult data collection demands.

The case study presented here assesses the vaporization rate of rolling oil on a coil of aluminum plate during its fabrication in a rolling mill. This was simulated through Finite Element Analysis (FEA) computer programs. The simulation captures the phase-change of the oil from liquid to vapor states. With this information, the concentration of oil vapor in the furnace atmosphere could be predicted. The concentration levels are used to determine the Lower Explosive Limits (LEL) for which the furnace operators are responsible. The reader should see the relativity of the simulation methods in this particular case study to many common furnace processes. Computer simulation lends itself to studies which can adjust or improve furnace processes without impacting production schedules or requiring extra data collection in production furnace environments.

## *Introduction*

Furnace maker Seco/Warwick of Meadville, Pennsylvania performed extensive research on the vaporization rates of oil to meet the requirements of NFPA 86 Standards for Ovens and Furnaces. This research resulted in insufficient information on the vaporization rates for the rolling oil used in various coil/foil annealers.

Aluminum coil/foil annealing utilizes process furnace systems with single coil modular furnaces or multizone furnaces with tight zone control. The coils of aluminum contain varying amounts of oil residue from the rolling process. The oil is retained by capillary action between the wraps of aluminum sheet. The oils vaporize into the furnace environment during the annealing cycle. Problems arise when the ratio of oil vapor to oxygen in the furnace rises to a combustible level, creating an explosion hazard. The lowest percentage concentration of oil vapor in air where ignition can take place is known as the Lower Explosive Level (LEL). Controlling the vapor concentration to remain below the LEL has always been a major occupational safety issue with furnaces of this type for obvious reasons.

The traditional method for controlling the vapor concentration has been to utilize a sweep gas in the furnace such as nitrogen or exothermic gas produced by the controlled combustion of natural gas. These furnace atmosphere gases provide some side benefits such as protection of the aluminum surface; however, the main purpose of the gas is to keep the oxygen level below the range where it will support the combustion of the oils.

The purchase of nitrogen or the generation of exothermic gas adds to the cost of production of aluminum sheet, plate, and foil. For that reason, a trend in industry has been to eliminate their use, substituting ambient air as a sweep gas. The object is to provide sufficient flushing action with the airflow to reduce the concentration of the oil vapor in the air below the LEL. One approach is to estimate the maximum rate of oil vapor being evolved from the coil, and set the air purge to continue at a volume appropriate for that rate.

It is advantageous to control the airflow into the furnace to provide an adequate margin of safety, while at the same time eliminating excess air for the greatest furnace efficiency. The air entering the furnace must be brought to furnace temperature and is as costly as heating the equivalent poundage of aluminum. Of course, there are many more pounds of aluminum in the furnace than there are of air being introduced, but the energy penalty for introducing unnecessary amounts of air into the furnace is significant.

The challenge has been to determine the proper airflow volumes to fit the above criteria. The surest way is to install a monitoring device in the furnace to sense the actual percentage of combustibles in the furnace and control the air purge accordingly. Using a monitoring device with a furnace in operation is expensive and requires careful maintenance to be reliable. Failure of the monitoring device would require a shutdown of the furnace, causing an expensive interruption of production.

The characteristics of most rolling oils can be readily obtained, including density, viscosity, and thermal properties. The heating characteristics of aluminum coils are also predictable by calculation. Although it appears simple on the surface, predicting the maximum rate of vapor evolution from a given coil carrying a given load of oil is surprisingly difficult. The heat transfer properties of the oil film between the wraps, as well as the heat removed by its latent heat of vaporization when it evaporates must be taken into account in the heating calculation in determining the instantaneous rate at any point in the cycle.

Seco/Warwick, as a designer of coil processing equipment, chose to undertake a study to determine a reasonably sized air purge system with adequate capacity. Actual empirical data on the subject is very difficult to obtain considering the number of variations in coil size and the amount of oil they contain. The number of variables in a coil annealing furnace would require a number of trials to be useful, and owners are understandably reluctant to tie up their equipment for testing at all, let alone for extended periods.

Therefore, a FEA computer program was used to aid in the prediction. A computer simulation would permit the furnace dimensions, changes in atmosphere, and loads to be easily modified to suit multiple setups. Even though the NFPA requires empirical data to meet safety standards, the results of this simulation can be used to approximate the amounts of oil vaporizing from the coils of aluminum and the LEL in the atmosphere.

Computer simulation methods are more often used for the analysis of parts or products in the field rather than for manufacturing processes. However, their application for process simulation can be valuable, providing understanding and insight to a system's response in an environment which is difficult to observe directly, and where it is costly to collect data remotely.

For instance, in this case study for vaporization of rolling oil between the layers of aluminum on a typical coil, observing or measuring the system is quite difficult due to the furnace atmosphere of 1,000°F (540°C) and an average air velocity of approximately 85 fps (26 mps). Rather than wiring sensors throughout the furnace to measure the concentration level of oil, which could be extremely difficult and costly, computer simulation is utilized. The computer simulation approach can be much easier to implement and can provide visual images of the system's behavior, even inside the layers of the coil. In addition, variations on furnace payload and heating or cooling cycle parameters can be easily modified on the simulation model to avoid interrupting manufacturing schedules.

### *Problem*

For the case study presented in this paper, a typical aluminum coil is studied. The coil overall outside dimensions are 48 inches (1,220 mm) in diameter with a 48 inch (1,220 mm) strip width. The aluminum plate is 1/4 inch (6.4 mm) thick and is wrapped on a steel mandrel, 16 inch (406 mm) outside diameter with 3/4 inch (19 mm) thick wall. Between the layers of aluminum, rolling oil is trapped in a layer 0.005 inch (0.13 mm) thick. Normally, six coils as described above are loaded on a furnace car and processed together as a payload. The simulation of a single coil is performed considering only one-sixth of the furnace volume for proper evaluation of vapor release and concentration in the furnace atmosphere.

The finite element model developed for this simulation is exhibited in Figure 1. This model utilizes two types of modeling symmetry to reduce the problem size: axial symmetry of the four foot long roll is assumed which permits the model to be two feet long, i.e., one-half of the roll length; and, due to the cylindrical geometry, an axisymmetric or body-of-revolution assumption permits a two-dimensional (2D) simulation model. In Figure 1, the centerline of the roll is labeled on the far left and overall dimensions are presented. In coloring, the steel mandrel is light blue, the aluminum is red, and the rolling oil is purple. On the right side of Figure 1 is a close-up view of the first wraps of aluminum on the mandrel and the trapped rolling oil layers. This model has 63 layers of rolling oil and aluminum from the steel mandrel to the outer diameter of the coil.

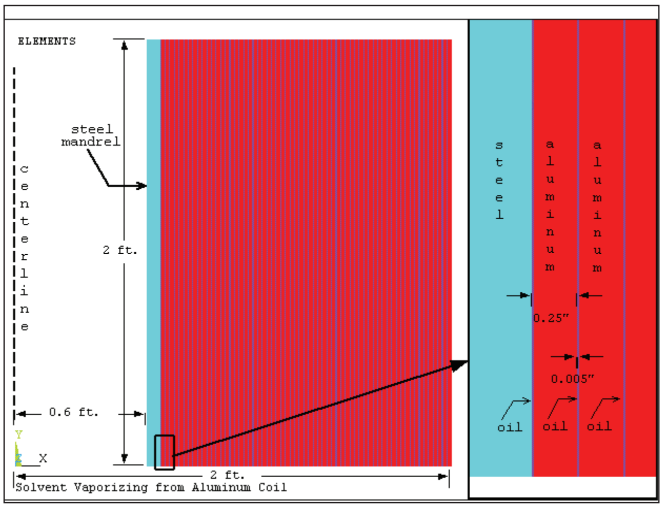

Figure 1. Simulation model geometry.

High temperature material properties for the solid materials, steel and aluminum, were taken from published handbook and textbook data tables.[1, 2] This data included the variation of the thermal conductivity and specific heat of the metals with temperature.

Heat transfer convection film coefficients, as shown in Figure 2, were computed as classical formulae for cylinders and flat plates.[3, 4] Forced convection was assumed on the outside surfaces and free convection circulation was assumed inside the mandrel.

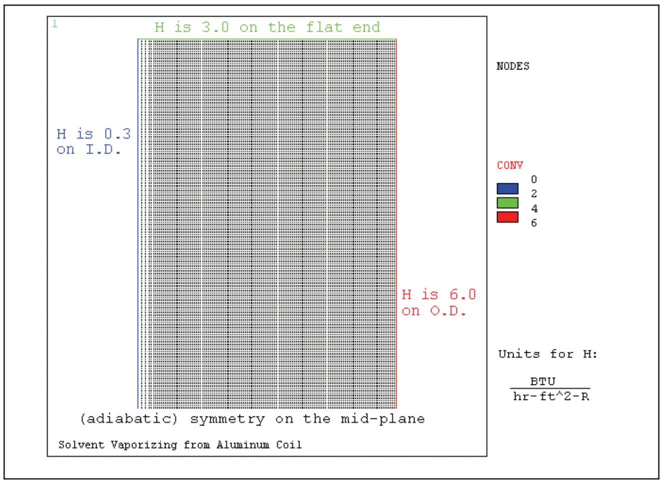

Figure 2. Node plot showing convection boundary conditions and symmetry plane.

Material properties for the rolling oil proved to be more difficult to find. To capture the process of vaporizing the rolling oil, the oil properties of density, specific heat, and thermal conductivity must be specified as they vary with temperature. Furthermore, to include the phase change from liquid to vapor states, the latent heat of vaporization was needed and, after the phase change, vapor properties of the oil are required. Handbook sources[1] and an Internet search[5] provided liquid properties, the boiling point (~400°F, 200 C), and the latent heat of vaporization (108 BTU/lb, 250 kJ/kg) for an example rolling oil. After vaporization the properties of air were used to characterize the rolling oil vapor.

A transient heat transfer simulation was performed with the room-temperature coil placed in the 1,000°F (540°C) furnace environment. Heat entered the coil model from the surfaces exposed to the hot air of the furnace by convection heat transfer and then the heat conducted through the layers, gradually heating the coil to its annealing temperature. The simulation covered a 12 hour duration of the annealing process which is also a typical cycle used in industrial practice.

### *Solution*

The evaporation of the rolling oil is determined in a post-processing operation (after the solution is completed). At each solution step, the volume of rolling oil is computed by the summation of all finite elements with an average temperature above the vaporization temperature. Using this data, the rate of vaporization can be computed. This data is shown graphically in Figure 3. The simulation shows that vaporization of the example rolling oil begins at ~0.75 hours during the furnace cycle and is complete at ~5.8 hours.

The liquid rolling oil evaporation data is then used to compute the rolling oil vapor concentration in the furnace. The furnace is treated as a "control volume" around the single coil. The calculations assume the volume is constant and that mass is conserved, so

$$\dot{M}_{AIR\text{-}IN} + \dot{M}_{VAPOR\text{-}RELEASED} = \dot{M}_{OUT}$$

For the simulation model, which is half of one coil, the local furnace atmosphere volume is calculated as 169.25 cubic feet (4.79 $m^3$), giving a maximum volumetric flow rate of 1,015.5 cubic feet (28.8 $m^3$) per hour. Using the density of air at 1,000°F (540°C) (0.027 $lb_m/ft^3$; 0.434 kg/ $m^3$) to represent the mixture of air and rolling oil