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ABSTRACT

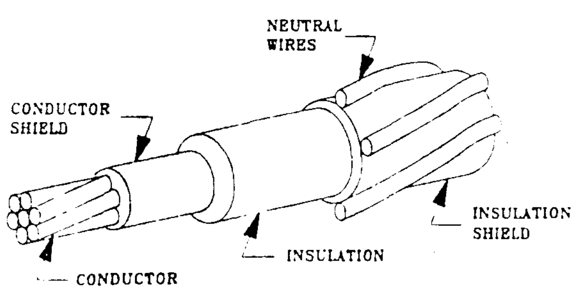
This paper addresses the problem of using simulation to model the radiant heat curing process of electrical cable production. The production process for underground residential distribution cable is presented and a simulation model of the bottleneck process is discussed.

THE PRODUCT

To get their product to the customer most companies use a delivery channel consisting of various combinations of manufacturers, wholesalers, retailers and the like. The delivery system for electricity utilizes electrical cables as the connection between the manufacturing utility and the customer. Just as there are many types of marketing distribution channels for the more standard goods and services depending on which system best fits the need, there are many different types of electrical cables, depending on such things as how much power must be delivered, who the customers are, where they live, and how reliable the power must be.

Here we are concerned primarily with a particular class of plastic insulated cables known as primary Underground Residential Distribution (URD) cable [1]. These cables are typically buried in the ground to provide an intermediate link in the electricity distribution chain. In general, the amount of power that can be conveyed by the cable is proportional to the product of its voltage and current ratings. The larger the electrical conductivity and cross-sectional area of the conductor and the thicker the insulation, the more power can be delivered by the cable. Of course, there is the usual trade off that more capability means more cost. The components of a typical URD cable are shown in Figure 1.

FIGURE 1



THE PROCESS

Two industry associations publish standards which dictate the requirements for mechanical and electrical properties of cross-linked polyethylene used in URD cable. The first of these, the Insulated Cable Engineer's Association, consists of a group of cable manufacturers that publish standards that may be referenced by utilities in their own purchase specifications [6]. The second group, the Association of Edison Illuminating Companies, is a group of cable users, primarily utilities, that publish standards which any utility may reference or adopt as their own [2]. In addition to these industry standards, utilities, especially the larger ones, write their own specifications for physical and electrical properties and cable performance.

One requirement of these specifications is a minimum degree of cure as measured by either a solvent extraction test or a hot creep test [6]. As the degree of cure is a function of the time and temperature to which the cable was subjected during curing this limit indirectly limits the maximum speed at which the cable can be processed [5].

Another limit on the maximum processing speed is the length of time required to cool the cable. To prevent the formation of voids, the cable must be cooled sufficiently before exiting the pressurized system. Experience has found that the maximum temperature allowable is somewhere around 200 degrees Fahrenheit at the hottest point in the insulating plastic layer. This normally occurs at the very inside of that layer since the cooling water cools the cable from the outside to the inside. In addition to sound engineering judgement, two specification requirements call for this limitation. First AEIC has requirements for maximum size and number of voids allowed in the insulation. Second, both AEIC and ICEA have limitations on the amount of partial discharge allowed in a cable. Partial discharge is electrical noise generated within voids in the cable insulation when voltage is applied to it. This is used as an indicator of the presence of voids.

In the case of the radiant heat curing process, there is also a limitation on the minimum speed at which a URD cable can be processed. This is due to the high cable surface temperatures which can be encountered as a result of the 750 to 850 degree Fahrenheit curing pipe temperatures. The polyethylenes used for the outer insulation shield begin to show deterioration at approximately 575 degrees Fahrenheit. If the cable is allowed to remain in the curing pipe too long, the surface can heat beyond this temperature and cause damage to the insulation shield material.

Outside of the curing/cooling process limitations, there exist others that control how a URD cable production line can be operated. Among these are the minimum and maximum output at which each extruder is capable of operating and the minimum and maximum speeds at which the other machines in the production line can run.

Generally URD cable manufacturers would start with the electrical rod as a raw material, produce smaller size wires by drawing it through dies with successively smaller holes, and then twist them together in the stranding operation to form the finished metallic conductor. The conductor shield, insulation and insulation shield, are each applied to the conductor in an extrusion process. The polyethylene, in pellet form, is fed onto a rotating screw where it is pushed through the heated barrel and melted. The pumping and mixing action of the screw acts to homogenize the molten plastic and move it to the front of the extruder where it enters the crosshead, so called because in it the melted plastic makes a right angle turn from parallel to the extrusion screw to parallel to the incoming conductor. Here the melted plastic wraps around the conductor, and forms a hollow tube over it as they exit the crosshead together. The conductor shield is applied first, by itself, followed generally by a few feet of air cooling. The insulation and insulation shields are then applied by two separate extruders feeding them through one common crosshead.

Immediately as the metallic conductor and plastic layers emerge from the insulation-insulation shield crosshead they enter the curing tube. As they travel through it, they are heated in a pressurized nitrogen atmosphere to a temperature sufficient to initiate the curing process. The nitrogen primarily serves two purposes. First it prevents gaseous by-products of the curing process from bubbling up and creating voids within the insulation. Second, it provides an inert atmosphere so unwanted chemical reactions do not take place during the curing. In the radiant heat/cure process, the heat is provided by passing electrical current through the walls of the stainless steel pipes enclosing the nitrogen. A typical system will have one to ten individually controllable heating zones to accommodate the varying heating requirements for different conductor size and plastic layer thickness combinations.

As the product leaves the heated pipe, it passes directly into a water filled cooling pipe where it is kept at the same pressure as in the heating pipe. Before the cable can exit the pressurized system, the plastic must be sufficiently cooled to prevent voids from forming due to gaseous by products of the curing process. Once cooling is complete, the product exits the curing/cooling system through a water seal and is wound up onto reels for further processing. The neutral wires are then twisted around the partially completed product. Finally, electrical and mechanical testing takes place before shipment to the customer to assure that specification requirements are being met.

THE COMPUTER MODEL

The algorithm used to model the radiant curing and water cooling portions of the URD cable manufacturing process is based on work reported by Boysen [4] in 1970. He describes a computer method for simulating the curing/cooling process of similar cable, only using steam as the heat source. In Boysen's model, the curing tube is divided into a number of sections along its length and the plastic extrusion thickness is divided into a number of annular rings. The length of the section is selected such that the individual section length is small enough to avoid large temperature changes in any of the plastic rings as the cable moves from one section of the heating tube to another.

The temperatures of each of the annular rings on the inside of the cable, in Boysen's algorithm, are recalculated at every section of the heating pipe. The new temperature is based on the temperature of the ring as it exits the previous heating section, the amount of heat being conducted into it and out of it by the ring inside and outside of it, and its own internal energy change over the time spent in the section. The time spent in each section, of course, is a function of the speed at which the cable is travelling through the process.

The outer ring, the one exposed to the steam, is assumed to always have a surface temperature equal to that of the steam, due to the condensation of the steam on the surface of the cable. The remainder of the heat transfer occurs similarly to the other rings. The metallic conductor receives its heat from the inner plastic ring. The equations for the heat flow from Boysen are summarized below.

Equation 1) Heat Flow from ring to ring

$Q= K\ A\ \Delta T/\Delta L$

Equation 2) Change in temperature for a given ring

$\Delta T= (1/M)\ \Delta Q_m/C_p$

where:

Q= heat flow (btu/h)
ΔT= temperature difference (deg F)
ΔL= distance in direction of temperature difference (inch)
A= area normal to direction of material flow ($inch^2$)
K= thermal conductivity (btu/h.ft. deg F)
M= mass of material
ΔQ_m= heat flow difference (btu/h)
Cp= specific heat

As Boysen explains, knowing the temperatures of the cable components as they exit the extrusion operation and enter the curing and cooling phases, and applying the above equations along with the concept of energy balance between the rings and sections, a new temperature can be calculated for each ring in each heating section. The equation for the new temperature of a given ring is shown below:

Equation 3) $T_n= T_o + \Delta Tt$

where:

T_n= new temperature of ring
T_o= old temperature of ring
ΔT= change in temperature for ring
t= time in section

Once the temperature of all the rings has been calculated for a given heat section, the degree of curing that has taken place as a result of the heating is then figured. Boysen [4] and Hercules [5] show curves of degree of cure versus time and temperature. The calculations for cooling are essentially the same as for heating except the heat flows are reversed since the outer medium is now cooler than the cable.

The model under study here generally utilizes the same assumptions and thermodynamic equations for heat transfer as explained by Boysen, once the heat has reached the surface of the cable.

The primary difference in calculations occurs in the method used to get the heat to the cable. Recall that the Boysen model assumes that since the steam condenses rapidly and directly on the surface of the cable, that the temperature of the surface of the cable is the same as the steam. In the case of the radiant cure process, the heat is transferred from the heated pipe to the cable surface primarily by radiation. Itaka et al [7] have described typical radiant heat transfer equations for two concentric cylinders. The function takes the following form:

Equation 4) $$Wr = \frac{S\,(T_1^4 - T_2^4)\,A_1}{1/E_1 + A_1/A_2\,(1/E_2 - 1)}$$

where:

Wr= heat transferred by radiation
S= Stefan Boltzman constant
T_1= absolute temperature of inner cylinder
T_2= absolute temperature of outer cylinder
A_1= surface area per unit length of inner cylinder
A_2= surface area per unit length of outer cylinder
E_1= emissivity of inner cylinder
E_2= emissivity of outer cylinder

The emissivities in the above are mainly empirical and are another source of possible error in, and adjustment to, the model.

Another variation that our model has from the Boysen model is the use of from one to ten insulated heating pipes, each of which can have its own length and temperature settings, and the use of a short, variable non-heated zone between the last heating zone and the cooling zone. The model allows the lengths to be input by the user.

MODEL APPLICATION

Boysen identifies three categories of applications for his model of the steam curing process which are also applicable to our model of the radiant cure process. One of these is the prediction of optimum operating conditions for the production line. Processing problems, product quality problems and productivity considerations are the primary issues in this case. Processing problems would include temporary limitations imposed due to equipment failures such as the loss of a heating zone or the reduction in output of an extruder to which the curing/cooling process must be matched. The model could be used to determine the temporary curing, cooling and line speed conditions necessary to match the limits.

Product quality problems for which the model would be useful would be where the cable failed to meet specification requirements and would require scrapping or reprocessing. Examples of scrap generating problems are overheated cables with scorched surfaces and undercooled cables with internal voids as evidenced by partial discharge measurements at the final electrical testing stage of production. The model could be used to examine the actual processing conditions used such as cure tube temperature, cooling water temperature, etc., as determined by production records, to determine if any variation in standard procedures that might be present were sufficient to have caused the problem. For product quality problems like undercuring, the model could not only be used to determine the possible reasons for the problem but also the conditions necessary for potential scrap reducing remedies like recuring by passing the cable through the curing/cooling process again.

As Bartnikas [3] points out, due to the amount of capital typically required to build this type of production line, it is economically essential that a company maximize productivity by maximizing production speeds. The model can be used to assist in developing target production rates used to establish Industrial Engineering Standards and subsequent standard costs of production, even for products which have never actually been produced.

A second application of cure calculation models cited by Boysen is the prediction of cure performance of new materials without the need for expensive plant trials. This is particularly valuable when production capacity is limited and profit making production must be forgone to accommodate experiments on new products. In the case of an organization with pilot facilities where material characteristics can be determined on small scale prototype equipment, the model can then be used to predict full scale production performance of the candidate materials.

The final application referred to by Boysen is the prediction of optimum process design. Here we are dealing with the design of new production facilities or the upgrade of current facilities. By being able to reasonably accurately predict production speeds for various combinations of curing and cooling lengths and temperatures, the outputs of these parts of the production process can be closely matched to the extruder outputs. This helps to minimize the capital investment necessary to achieve desired production rates. It also may help to maximize productivity for an entire cable production facility since the curing/cooling process is typically the bottleneck operation.

The ability to predict production speeds through the use of the model has other potential applications in addition to those mentioned by Boysen. For instance estimates can be made of production costs. Once the costs are predicted, business problems like how many of which products are best to make, what is the potential return on the capital investment, and what are the best ways in which to schedule production of orders, may be examined.

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