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Featured Research

Measuring Molten Glass Temperature

Smart Sensors Give Glassmakers Warm Fuzzies

The first glass used by humankind was obsidian, made naturally by the rapid cooling of molten rock in the throat of a volcano. Hard and durable, but easily worked by chipping and hammering, obsidian became the raw material for scrapers, knives, spear points and arrowheads 75,000 years ago. Superseded by metal implements, obsidian tools and weapons passed into history, and it was only five thousand years ago that the Sumerians of ancient Mesopotamia were able to create a temperature high enough to melt pure silica sand to form their own glass.

Given enough heat, molten silica flows like lava. What was probably problematic for the Sumerians, though, is that unevenly cooling glass, like hardening lava, can crust or malform. Modern glass manufacturing methods require carefully controlled temperatures. The inaccuracy of temperature sensing methods, however, make maintenance of a constant temperature technologically challenging. Improvements in temperature monitoring would save enormous amounts of fuel and reduce greenhouse gas emissions by improving manufacturing efficiency. As well, such improvements could be applied to any process in which temperature control was critical, including metal manufacturing and heat treatment of products.

The researcher is making glass from material that simulates a nuclear waste to reduce the waste volume and to generate a durable waste form for long term storage.

INEEL scientists are creating a temperature sensor and control system that will integrate the most expert of human experience with the objectivity of numerical logic. If the project is successful, U.S. glass, aluminum, steel manufacturers and chemical refiners, as well as the DOE, will benefit from improved temperature control with reduced waste, decreased maintenance of the furnaces and less down time for glass-melting furnaces.

THE MAKING OF GLASS

The modern glass-making process has two essential stages: melting the raw material in a tank until bubbles and streaks in the melt disappear, then cooling the glass in a long channel called the forehearth. Temperatures in the melt tank vary with the composition of the raw material. Once the glass flows into the forehearth, careful temperature control becomes essential for shaping the raw material into sheets, molds, and the multitude of glass objects in our lives.

"Fuzzy logic, observation and control puts rigor into human intuition."
Charles Tolle

"The forehearth is a shallow channel or a ditch through which glass is moved after the temperature is lowered," says Frank Woolley, former manager of melting research at Corning, Inc. "Glass is a poor conductor of heat, so the outside of a mass of glass may cool fast, while the interior stays the same." However, the glass-forming process works best when the fluidity, and therefore the temperature, of a mass of glass is uniform.

"Since there is already a large drop in temperature as the glass leaves the melt tank to go into the forehearth," Woolley explains, "temperature measurement at the forward end (the forehearth) is most critical." If the temperature is not uniform, sometimes as much as fifty percent of the batch is wasted. In the glass-making industry, there are three common temperature control methods: the thermocouple, optical pyrometry, and the experienced glassmaker.

In a thermocouple, two wires of different metals are connected in an electrical circuit. One wire is held at a known temperature, and the other varies with the temperature of the melt. A current that is proportional to the temperature difference flows between.

Thermocouples are common and inexpensive in the industry, but they decay because of chemical contamination. As a result, after a while they estimate the temperature inaccurately and have to be replaced, a process that slows production. In the meantime, the glassmaker adjusts the temperature unnecessarily, adding too much or too little heat.

Optical pyrometry, another widely-used method, relies on the varying wavelength of energy emitted by a glowing body. The hotter the glass, the shorter the wavelength of the infrared radiation emitted. In a sense, optical pyrometry is a rigorous way of measuring what a human observes by peering into the melt tank — the color of the molten glass indicates its temperature.

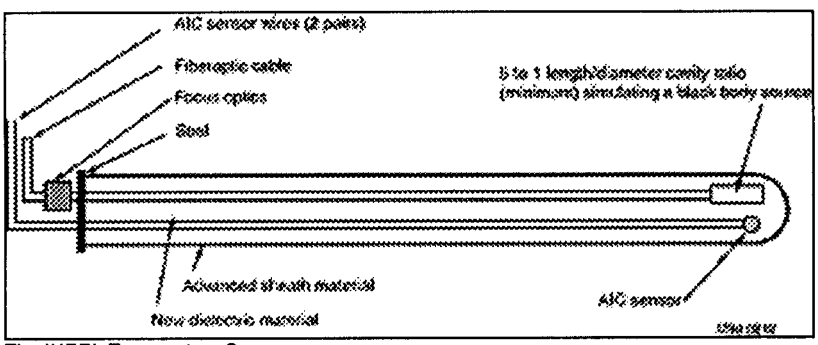
Optical pyrometry, however, also becomes unreliable after a while. Volatile matter from the molten material and environmental dust cloud the window through which the measurements are made. This causes the instrument to record inaccurate temperatures again, costing the manufacturer in wasted energy and scrapped product.

The third common temperature control method is the experienced glassmaker, who learns to account for unreliable instruments and adjusts the controls according to acquired skills.

THE IMPROVED TEMPERATURE SENSOR

Suppose a manufacturer could have a thermocouple, an optical pyrometer and an experienced, expert glassmaker side-by-side as every batch of glass came through the melter into the forehearth. Suppose too, in this ideal world, that the pyrometer and the thermocouple could be insulated against the corrosion and clouding that affect their accuracy. And finally, imagine that all the information from these three "sensors" could be combined into an automatic control-system that ensured the glass was always at the right and uniform temperature in the forehearth. This system would save energy and improve efficiency by preventing waste.

Nancy Carlson, Arthur Watkins and Charles Tolle of the INEEL are working with Collins Cannon of AccuTru International Corp. of Kingwood, Texas, to design and produce such a system. It begins with a novel temperature sensor that can be immersed in the molten glass itself. The sensor contains both a thermocouple and an optical pyrometer enclosed in an elongate sheath made of a new ceramic material resistant to the corrosion that damages traditional sensors. The thermocouple comes from AccuTru International, and the optical sensor is a new design from INEEL.



The INEEL Temperature Sensor

A pyrometer measures thermal radiation, but the amount of radiation emitted at a given temperature must be compared with the amount emitted by a standard, called a blackbody radiator. The ratio of the two values indicates temperature. As the blackbody radiator ages, the ratio changes and the instrument becomes unreliable. The INEEL design overcomes that difficulty by measuring the radiation from a simulated blackbody radiator, providing a truer value for the temperature of the glass.

In addition, the infrared radiation being measured arises from the interior of the ceramic sheath, eliminating the need for a window. In these ways, the INEEL temperature sensor is not affected by the changes that bedevil conventional pyrometers.

However, no matter how accurate the sensors, they cannot perfectly measure reality. At any given sampling site, the real temperature will differ from the sensors' readings. Mathematically refining the sensor information can improve confidence in the estimated temperature. A method of analysis called "fuzzy logic" will be the backbone of the temperature control system being designed at the INEEL. The fuzzy logic control strategy will incorporate an experienced, human operator's "rules of thumb" used to maintain the furnace, in addition to temperatures taken by the INEEL-designed pyrometer and thermocouple sensor.

First, computer-coded observers will use both the INEEL optical and AccuTru thermocouple sensor elements to determine temperature, but will assign a level-of-confidence to the measurements based on built-in knowledge from human operators. An observer reconciles the temperature reading coming from the sensors and the confidence value of each, thereby arriving at a more precise temperature estimate that includes information about the quality of the instrument. For example, a brand-new thermocouple may have a level-of-confidence close to 100 percent, whereas for a five-year-old pyrometer, the level-of-confidence may be only 50 percent. The observer then calculates a weighted value for the particular temperature measurement and feeds it into the computer control system.

In addition to temperature, other factors in glass technology will be included to enhance the effectiveness of the observer: the effect that the volume of material in the tank or forehearth has upon temperature gradients; varying viscosity; the control that chemical composition exerts upon viscosity or thermal conductivity; as well as the knowledge of the operators and engineers who may have a "feel" for whether the glass-making process is working satisfactorily.

Second, all these pieces of information will be used to establish rules for automatic control of the melting and forming process. Side-by-side with expert industrial partners in the glass industry, the INEEL scientists and engineers will learn the process of glass manufacturing and incorporate the knowledge into the other part of the system, the computer-coded controller. Ultimately, the researchers hope to produce glass that conforms to industrial standards without persistent round-the-clock intervention by human operators. "Fuzzy logic, observation and control," says Charles Tolle, "puts rigor into human intuition."

That rigor translates into more than just improved quality of each glass batch. The typical glass melting furnace uses much more energy to melt the batch than is theoretically necessary. Some of that energy goes out of the smoke stack and elsewhere into the environment around the furnace, but some of it is lost because of inaccurate temperature measurement and control. Tightening control of the process will save fuel, reduce emissions and benefit both the environment, the DOE, and INEEL's industrial partners.

For a more technical discussion of the technology, click here.

Written for INEEL Research Communications by Robert Evans.