First Simulation of PID Controller Helps Validate New Hazardous Waste Treatment Technique

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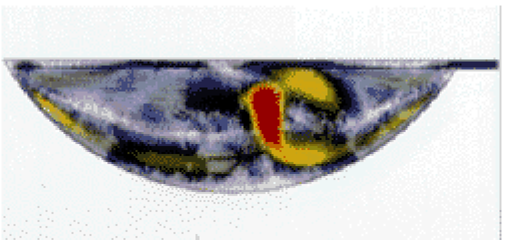

The velocity vectors without metal pool. The highest temperatures in the model are the areas of the slag directly beneath the electrodes, since this is where the highest heat flux condition was imposed.

What is believed to be the first successful computational fluid dynamics (CFD) analysis that incorporates a proportional-integral-derivative (PID) controller is helping to validate a new hazardous waste disposal process. The new process uses a thermal plasma arc to transform soil contaminated with radioactive waste into a glass-like substance suitable for permanent storage.

A CFD code that calculates electrical fields, heat transport, and natural convection all coupled together is used to simulate the soil melting process. The software allowed INEL engineers to write a PID subroutine that plays a vital role by following the specified electrical power curve.

Contaminated soil presents a particularly difficult cleanup problem since it is often present in large volumes and can be spread by water and wind. The Idaho National Engineering Laboratory (INEL), under the direction of the U.S. POE office of Technology Development is working on optimizing a soil melting process that transforms contaminated soil into a glass-like substance suitable for permanent storage. Radioactive soil would be dug up and transferred into a melter located at the contamination site and then processed at extremely high temperatures. Another approach that has been investigated is in-situ vitrification in which soil is vitrified in place without exhumation and without a melter. This technology is also under consideration as a method of reducing the volume of and storing of municipal waste.

A thermal plasma arc is used to pyrolyze and combust organic materials and melt residual organic compounds. To start the process, electricity is passed through a graphite powder located between the electrodes. Electrodes melt the soil at which point it attains sufficient electrical conductivity so that it generates Joule internal heat. When the graphite powder has heated up the surrounding soil, a pool of molten soil that can conduct electricity is formed. Using a plasma arc code, INEL engineers calculated that, in a typical contained melter, half the heating would be through convection and half by Joule heating.

The waste is vitrified into a substance that looks like red hot lava and is poured for permanent storage into containers of any desired shape. Upon cooling, the radioactive particles are incorporated into a glass-like substance, a condition that is suitable for long-term permanent storage. The key advantage of vitrification is that the resulting solidified substance cannot be translocated by water, wind or other erosion factors. One proposal is for the molten soil to be poured into 55 gallon metal drums and buried.

Although thermal arc technology has been utilized in metallurgical processes during the past two decades, only recently have there been efforts to evaluate the feasibility of plasma applications to waste treatment. This technology offers several advantages over the flame-based thermal processing methods which are currently used for this task. First of all, conventional thermal methods do not provide for permanent encapsulation of heavy metals and radio nuclides in a non-leachable final product.

Secondly, the much higher temperatures, up to 10,000K, and energies generated by the thermal arc method greatly increase the amount of volume reduction to 40% to 60% of its original volume. The gas given off is filtered so that no radioactive or hazardous particles are released to the atmosphere. The vitrification process also increases the density of the soil from 1600 kg/m^3 to 2300 kg/m^3. The result is a 50% decrease in volume.

The key to the economic viability of this process is optimizing the amount of soil that can be vitrified per unit of electrical power consumption. In full production a soil melter would draw in the area of 2 to 4 megawatts. A pilot unit draws about 300 kW. The optimization process demands that parametric studies be performed with different types of soil, different power supplies, different types of electrodes and electrode geometries, etc.

Pilot-scale testing, although indispensable, is a very expensive and time-consuming design tool. For that reason, INEL management believes that computer simulation is essential to establishing the validity of this process. By performing parametric analysis with the model and using optimization techniques, designers can modify or develop designs that reduce the construction and operating costs of the facilities. The model can also aid engineers in understanding the causes and effects of physical processes occurring with plasma arc facilities.

INEL engineers selected FIDAP CFD software from Fluent Inc. to simulate the soil melting process. FIDAP can calculate electrical fields, heat transport, and natural convection all coupled together to simulate the Joule heating that is critical to the melting process. The software also provides the unique capability of controlling power input as a boundary condition with a PID controller that can be programmed in FORTRAN.

INEL engineers have modeled several different contained melter and in-situ vitrification designs. In a typical model, one-half of a two electrode model was used since symmetry can be assumed for the temperature and electric fields. This 2D model requires 5 equations: conservation of mass, conservation of momentum in x, conservation of momentum in y, conservation of energy and electrical field equations. FIDAP's transient capability is used to track the melting process over time. The model has a radiation and convection boundary condition representing the plasma arc.

Size of the model was chosen to represent typical pilot testing equipment in two dimensions. The electrodes have a 1.10 m spacing and are 0.10 meter thick. The assumption was made that there is initially a small rectangular region between the electrodes in which the soil is at its melting temperature. This is done to simulate a graphite starter path that melts very quickly with the electrical current applied. The conductivity is high enough to generate heat in the soil. The initial melt zone extending between the electrodes is 10 cm thick and is covered with 10 cm of soil. The remainder of the soil is initially at ambient temperatures. All external surfaces of the model are assumed to be adiabatic.

Electric field and heat transport equations are solved during the heatup. To start the simulation, an initial voltage of 120V is applied to the electrode as a boundary condition. A voltage boundary condition of zero is applied along the right side of the model to insure symmetry of the electrical field since the other electrode would be at -120V. The simulation starts with an initial power of 50kW and follows a ramp up to 150kW at a time of 5000 seconds. In order to control the power input, a voltage boundary condition through the electrode was implemented and maintained by a PID controller implemented in a FIDAP user subroutine. After some trial and error, gains were found that controlled the power well.

Also, trial and error showed that it was necessary to turn the gains down from their original values between 2,000 and 5,000 seconds. This was implemented by linearly decreasing the gains from

90% of their original value at 2,000 seconds to 10% of their original value at 5,000 seconds. At a time of 5,000 seconds when the power ramp levels off, the PID controller was implemented to maintain a steady state condition. The PID controller calculates the power input to the melter and changes the voltage as necessary to follow the ramp. The FORTRAN program controls voltage boundary conditions as a function of time as the flow of transients proceeds. When writing the user subroutine that links FIDAP in implementing the controller, it was also necessary to calculate the Joule Heat source term. FIDAP calculates this internally but it was not available to the user subroutine.

The results of the simulation clearly depict the development of the melt. Temperature contour plots at 4000 seconds show the melt growing upwards and downwards from the initial temperature profile. At 7500 seconds, all of the top right hand corner of the soil is melted and the melt is continuing to progress downwards. The maximum temperature starts at about 1500K from the initial conditions and increases to 2450K at the final time of 8,000 seconds. The maximum temperature starts to level off at the end of the simulation. Voltage contours show that the initial voltage of 120 is quickly changed by the PID controller to about 400V within about 10 seconds. The maximum voltage was about 440 V at 500 seconds. The voltage steadily dropped from 500 seconds until the end of the simulation where the necessary voltage was calculated to be 110V. The reason the voltage dropped during the simulation is that the resistance in the melt decreases as the melt grows.

INEL will continue to model different types of melters using CFD. The current project is a DC non-transferred arc design in which the arc goes across the melter, arcing from one electrode into the soil to the other electrode. By contrast, a planned DC transferred arc design will have the arc going from the graphite electrode down through the soil to the other electrode at the bottom of the melter, thereby allowing for higher amounts of melting in a shorter time. Other Department of Energy projects using CFD involve modeling the storage of dry nuclear fuel and the relocation of a nuclear core at a power plant. Clearly the use of CFD is dramatically improving handling of hazardous materials by allowing a wide range of different scenarios to be evaluated while reducing the need for expensive and time-consuming testing.