Mitigation of Greenhouse Gas Leakage from Oil and Gas Wells

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Abstract:
Pre-existing wells and well bores are high-permeability pathways through the earth's crust and thus are at elevated risk as a path for CO_2 leakage. Although current well closure and abandonment technologies appear sufficient to contain CO_2 at most sites, many wells may suffer from a variety of factors that limit their integrity and lead to continued long term release of dangerous greenhouse gases. To permanently seal wells emitting greenhouse gases Seal Well has developed technology to provide *in-situ* molding of a seal between the well casing and cemented annulus. A low melting point bismuth-tim alloy is heated and allowed to flow into the fissures, cracks and cavities; on cooling the material expands to provide a permanent seal. To accelerate development and deployment of Seal Well's technology, a computational model has been developed using COMSOL Multiphysics to analyze the conjugate heat transfer occurring during heating and cooling and the thermomechanical stress developed during solidification.

Keywords: Conjugate heat transfer, Conduction, Convection, Stress analysis

1. Introduction

Recognition of the increasing risks of global warming has increased interest in developing technologies to reduce greenhouse gas (GHG) emissions. Pre-existing oil and gas wells and well bores represent highly permeable pathways for leakage of greenhouse gases; in Alberta, Canada alone leaks have been estimated to provide the equivalent of 3.5 million tonnes of CO_2 per annum. In addition to abandoned wells without plugs, gas leakage may occur when the integrity of wells is compromised by a variety of factors including incomplete construction or failure of the cement plug, overpressure in the well and corrosion of the well plug. Gas leakage due to surface casing vent flow (SCVF) through the cemented annulus between the production casing and the well bore wall has been estimated to occur in 14% of Alberta wells. Solutions to SCVF are both difficult and expensive to implement. To prevent long term damage, permanent solutions for sealing wells are required with minimum service lives of 3000 years being sought for gas sequestration projects.

The technology developed by SealWell uses a low melting point bismuth-tin alloy that is molded *in situ* to produce a permanent seal. The process is shown schematically in Figure 1.

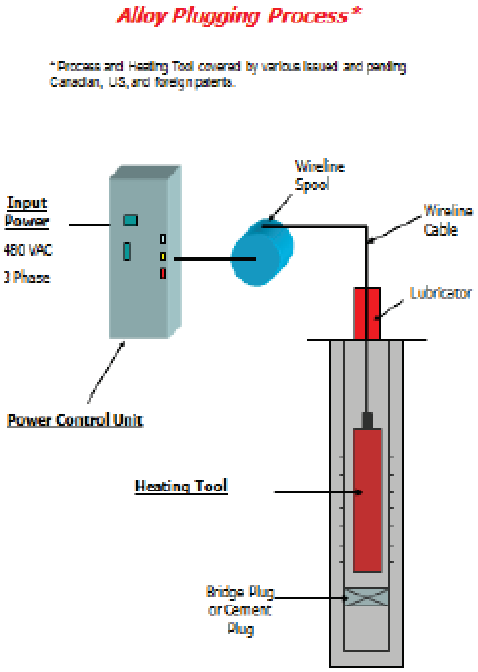

Figure 1: Schematic of SealWell technology for sealing of oil and gas wells.

A heater is lowered into the wellbore to melt the bismuth-tin alloy. Due to the low viscosity and high specific gravity the molten alloy flow inot fissures. Factures and channels and displaces any fluids present. As the alloy solidifies it expands volumetrically by approximately 1% to produce a permanent seal. Expansion in the radial direction is encouraged by applying a modest pressure through a surface water pump during the cooling/solidification process.

2. Problem description

Successful development and deployment of the well sealing technology relies on two effects: heating to melt the bismuth-tin alloy in sufficient volume to infiltrate the porous structure around the well head, and the development of a stress distribution due to solidification of the alloy that has sufficient strength to provide a permanent seal. To support development of the technology, computational analysis of these effects was performed using COMSOL Multiphysics.

The transient conjugate heat transfer problem associated with melting the bismuth-tin alloy *in-situ* included the effects of heat transfer due to conduction in the solid domains and convective flow in the fluid domains of the molten alloy and surrounding fluids.

The residual stress distribution developed due to volumetric expansion of the molten material on solidification included the effects of temperature dependent material properties in the solid domains and elastic/plastic material properties. A top pressure to induce radial flow of the molten alloy due to the presence of pumped water was included. The resulting residual stress distribution was used to predict the strength of the seal on solidification.

3. Computational model

Heat transfer within the solid domain is described by the heat equation:

$$\rho\, c_p \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T\right) \qquad (1)$$

Where, ρ is the density of the solid or fluid material, c_p is the specific heat capacity, T is the temperature, and λ is the thermal conductivity.

In the fluid domain, the physics are described by the conservation of mass, momentum, and energy according to the following equations:

$$\nabla \cdot \left(\rho\ \mathbf{u}\right) = 0 \qquad (2)$$

$$\rho\ \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left(\eta \left(\nabla \mathbf{u} + \left(\nabla \mathbf{u}\right)^T \right) - \frac{2}{3} \eta \left(\nabla \cdot \mathbf{u}\right) \mathbf{I} \right) + \rho\ \mathbf{g} \qquad (3)$$

$$\nabla \cdot \left(-k \nabla T\right) = Q - \rho\ c_p \mathbf{u} \qquad (4)$$

The viscous heating and pressure work terms are neglected in the energy equation. In the above equations, ρ is the density, $\mathbf{u}$ is the velocity vector, p is the pressure, η is the dynamic viscosity, $\mathbf{g}$ is the gravitational acceleration vector, k is the thermal conductivity, T is the temperature, Q is a heat source term, and c_p is the specific heat capacity. The viscosity, thermal conductivity, and specific heat capacity are functions of temperature, while the density is a function of both temperature and pressure. A heat flux is applied to the heater and temperature boundary conditions are applied to the external boundaries of the well. Appropriate material properties are assigned to the different domains of the well structure associated with steel liner, concrete plug, aluminum heater, surrounding soil, bismuth-tin fluid and well fluid.

The residual stress generated during solidification was calculated using the integrated solid mechanics solution capabilities to solve the equilibrium equation:

$$\nabla \bullet \boldsymbol{\sigma} = 0 \qquad (5)$$

with the following constitutive relation:

$$\boldsymbol{\sigma} = \mathbf{C} : \boldsymbol{\varepsilon}_{el} \qquad (6)$$

where:

$\mathbf{C}$: elastic tensor

$\boldsymbol{\varepsilon}_{el}$: elastic strain

Elastic strain is defined by the following set of relations:

total strain: $\boldsymbol{\varepsilon}^T = \boldsymbol{\varepsilon}_{el} + \boldsymbol{\varepsilon}_{th} + \boldsymbol{\varepsilon}_{dil}$ (7)

thermal strain: $\boldsymbol{\varepsilon}_{th} = \alpha_{th}\left(T - T_{ref}\right)$ (8)

dilatational strain: $\boldsymbol{\varepsilon}_{dil} = \alpha_{dil}\theta_{SiC}$ (9)

The geometry of a well and Seal Well's heating tools are cylindrical, allowing use of a 2D axisymmetric model, Figure 2.

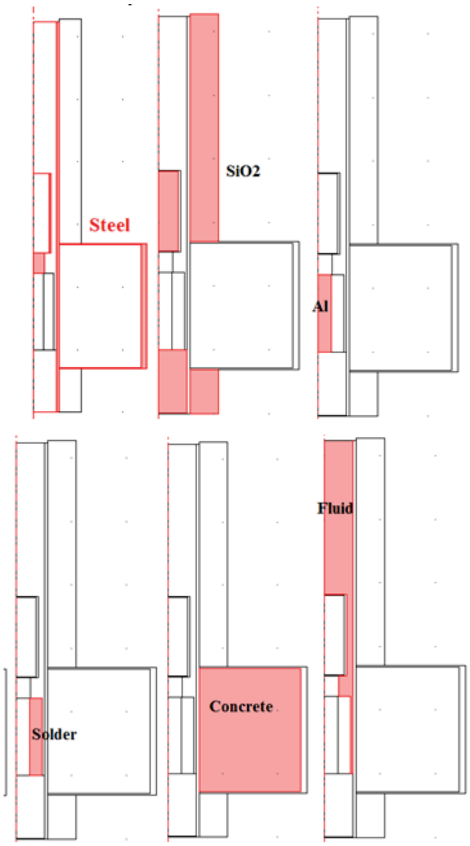

Figure 2: Axisymmetric model of well with heater unit in place which shows material domains.

A second analysis geometry was developed to study the solidification of the pooled bismuth solder once the heater unit is removed from the well as shown in Figure 3.

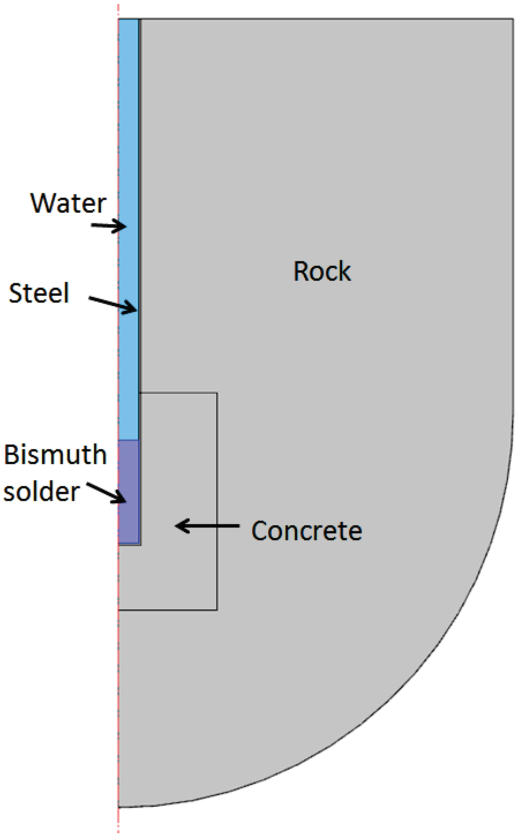

Figure 3: Axisymmetric model showing material domains for the case when the well has the heater unit removed and the liquid bismuth solder is able to pool at the bottom of the well

4. Results

Initial analyses were performed for the conjugate heat transfer problem by considering heat transfer due to conduction and convection coupled with a solid to liquid phase change in the bismuth-tin alloy. Results of the temperature distribution across the materials in the well structure using the transient conjugate heat transfer model are shown in Figure 3 and the average temperature of the solder as a function of time with and without inclusion of the solid to liquid phase change are shown in Figure 4.

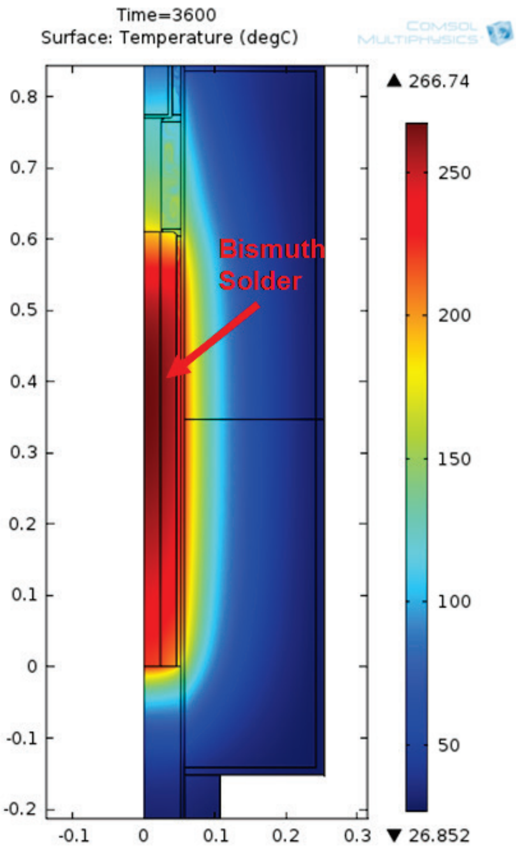

Figure 3: Temperature distribution in well head with heater unit installed after 3600 seconds (1 hour).

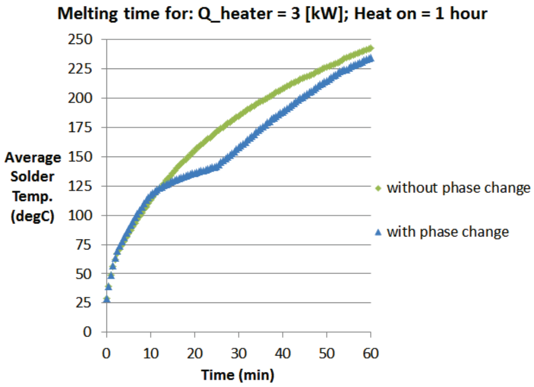

Figure 4: Average temperature history of the bismuth-tin solder as a function of time with and without the effect of solid to liquid phase change.

After withdrawal of the heater the molten bismuth-tin alloy solidifies during which time it expands by approximately 1%. The effect of the expansion can be seen in Figures 5 and 6 that show the variation of the maximum and minimum temperature of the bismuth-tin alloy as a function of time and the compressive stress at the interface between the bismuth-tin alloy and the steel well liner tube: as the alloy transitions from liquid to solid the compressive radial stress at the interface increases significantly.

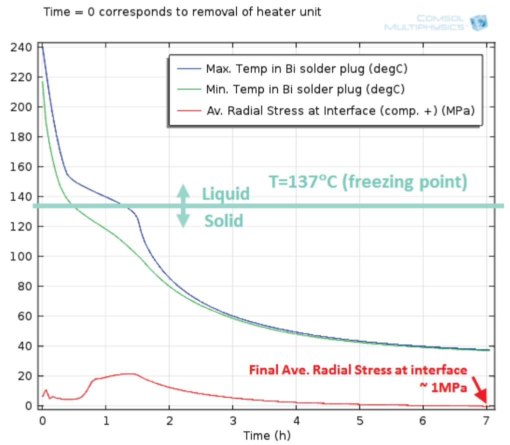

Figure 5: Temperature history of bismuth-tin alloy and radial stress at interface with steel tube.

The resulting distributions of plastic strain and residual compressive stress in the well seal region due to the solidification process are provided in Figure 7 and 8.

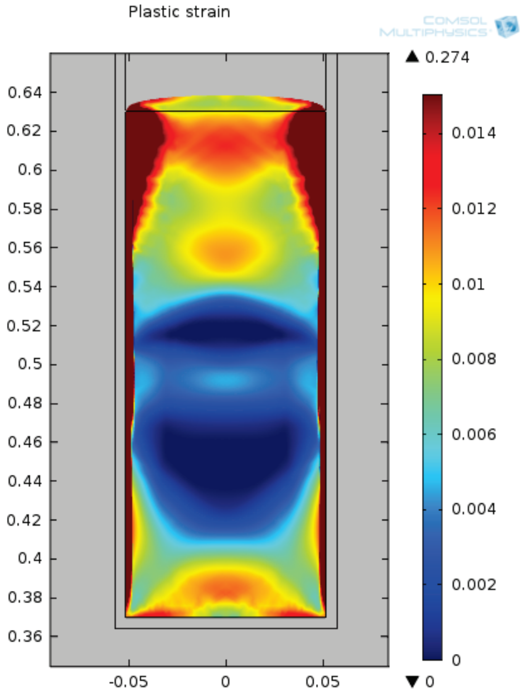

Figure 7: Plastic strain distribution in well seal region due to solidification of bismuth-tin alloy

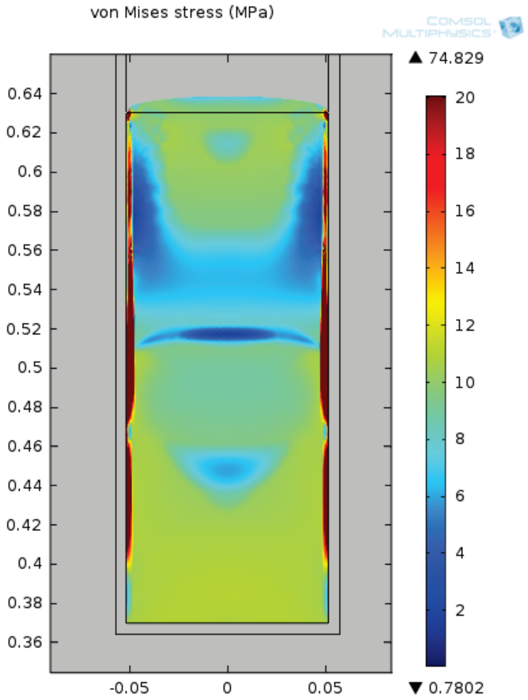

Figure 8: Von Mises stress distribution in well seal region due to solidification of bismuth-tin alloy

5. Summary

This work has demonstrated the use of computational analysis performed by COMSOL Multiphysics to analyze the conjugate heat transfer problems associated with melting and freezing of a bismuth-tin alloy in the vicinity of a oil or gas well head, and prediction of the residual stresses developed during the solidification process. The results of the temperature predictions are comparable to experimental measurements taken during practical demonstration of the technology. The results of the residual stresses developed during the process demonstrate that high compressive stresses can be developed that are suitable for providing a permanent seal on abandoned oil and gas wells.