

SINDA/FLUINT STRATIFIED TANK MODELING

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Introduction

A general purpose SINDA/FLUINT (S/F) stratified tank model was created and used to simulate the Ksite¹ LH₂ liquid self-pressurization tests as well as axial jet mixing within the liquid region of the tank. The S/F model employed the use of stratified layers, i.e. S/F lumps, in the vapor ullage as well as in the liquid region. The model was constructed to analyze a general purpose stratified tank that could incorporate the following features:

- Multiple or singular lumps in the liquid and vapor regions of the tank
- Real gases (also mixtures) and compressible liquids
- Venting, pressurizing, and draining
- Condensation and evaporation/boiling
- Wall heat transfer
- Elliptical, cylindrical, and spherical tank geometries

Extensive user logic was used to allow for tailoring of the above features to specific cases. Most of the code input for a specific case could be done through the Registers Data Block.

SINDA/FLUINT Stratified Tank Setup

The stratified tank was modeled via a series of S/F layered lumps (TANKS) in the vapor and liquid regions. The number of layers in the vapor region need not be the same as the number of lumps in the liquid region. The tank wall was also modeled under the same premise, i.e. that the number of thermal nodes in the vapor wall region need not be the same as the number of thermal nodes in the liquid wall region. Furthermore the nodes and lumps in the vapor region need not have a one to one correspondence. This was also true in the liquid region. Wall node volumes were determined by the number of thermal nodes input for the vapor wall and liquid wall regions respectively. Vapor wall node volumes corresponded to, or were “one to one” to, the *initial* “equal” vapor fluid volumes that would be calculated based on the input number of wall vapor nodes. Similarly, liquid wall node volumes corresponded to, or were “one to one” to, the *initial* “equal” liquid fluid volumes that would be calculated based on the input number of wall liquid nodes (Figure 1). Therefore wall node volumes were not necessarily uniform values in the vapor region or liquid region.

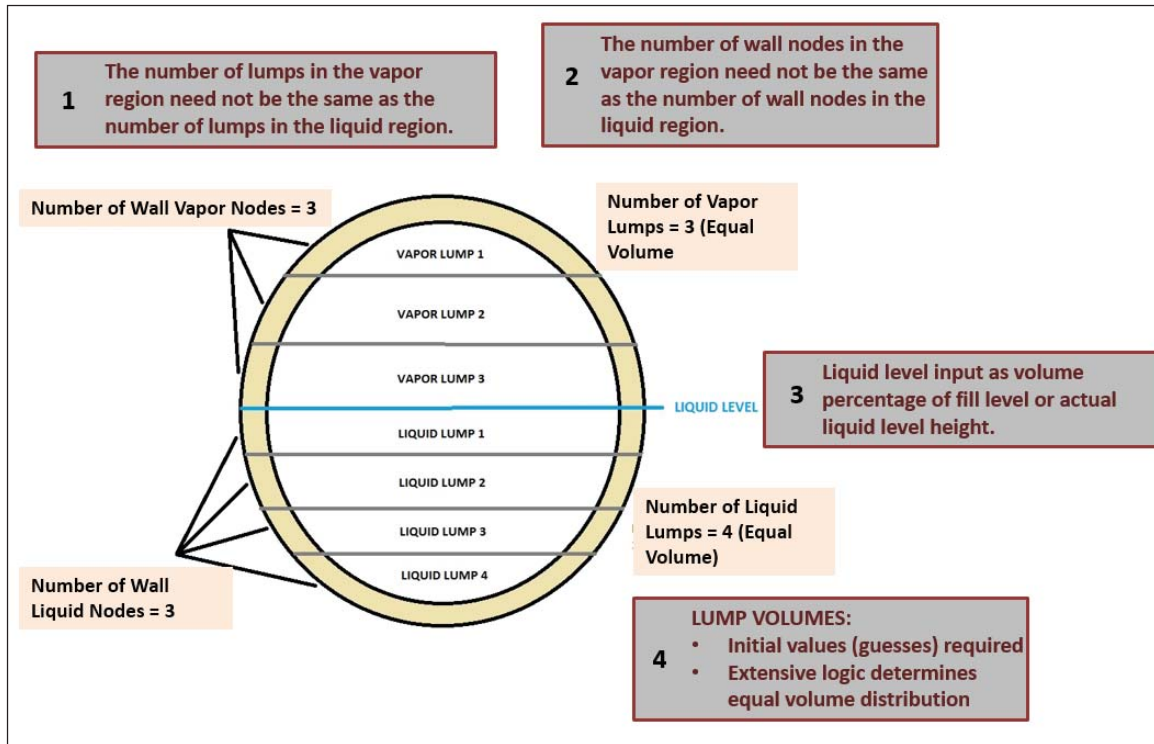


Figure 1: Tank Wall Node Generation

Although initial values for the lumps' volumes were required as input in S/F, these values were only guesses. Extensive logic incorporated in the S/F user logic blocks determined an equal volume distribution in the vapor region and an equal volume distribution in the liquid region. The volumes were determined through user input in the Registers Data Block such as geometric tank dimensions, liquid level, as well as the input number of vapor and liquid lumps. The liquid level could be input as either a volume percentage of fill level or actual liquid level height.

The heat rate was imposed on the outer surface of the tank wall nodes. Axial conduction along the tank wall was modelled (Figure 2). Although radial conduction was ignored in this model, it could easily be implemented. The heat leaves the wall and enters the fluid via an imposed heat rate calculated using free convection boundary layer empirical relations (see **SINDA/FLUINT Boundary Layer Analysis**).

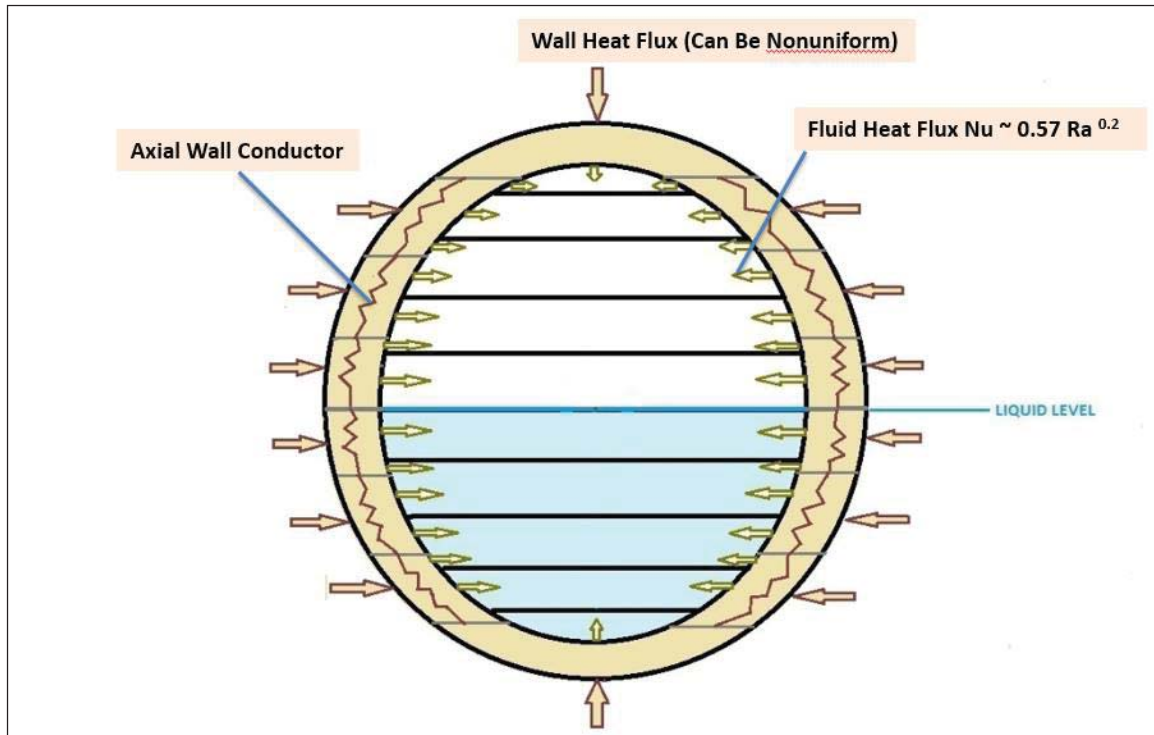


Figure 2: Stratified Tank Heat Transfer

Volume Flow Rate Connectors (VFRSETs) were placed between the layered lumps in each region. User logic determined the volume flow rate through these connectors so that the volumes of the lumps in each respective region remained constant within a small percentage. This process avoided lumps from becoming too small or too large relative to one another, and consequently avoided the problem of having very small lumps to somehow “disappear”. Making a lump “disappear” was not practical or feasible to do in S/F. S/F IFACES were also placed between the layered lumps in each region. The S/F IFACE was a device that insured the pressure of *all* the lumps within the tank remained constant (minus buoyancy effects). The IFACE acted like a membrane between lumps that allowed the lumps to expand or contract as the thermodynamics dictated. Maintaining constant volumes in the vapor and liquid regions respectively created a model that was similar to a “finite volume” approach so that the lump geometric locations did not dramatically fluctuate. The volume flow rates between lumps were determined and set by user logic based on the flow physics of the tank, i.e., whether the tank was venting, pressurizing, or draining. Other dynamics that would yield volume flow between the lumps included evaporation/boiling, condensation, and axial jet mixing.

SINDA/FLUINT Boundary Layer Analysis

The thermal boundary layer that formed along the tank wall was modeled empirically using correlations for convection. These correlations could either be for forced or free convective flow. The cases modeled employed only buoyancy driven flow and therefore the empirical relationships were for free convective flow along a vertical wall at constant heat flux. Any empirical relationship could easily be employed by the user. The logic also checked for turbulent or laminar conditions. The following correlation was used¹:

$$\mathbf{1.a} \quad \text{Nu} \sim 0.57 \text{ Ra}^{(0.22)} \quad 10^{13} < \text{Ra} < 10^{16}$$

$$\mathbf{1.b} \quad \text{Nu} \sim 0.6 \text{ Ra}^{(0.2)} \quad 10^5 < \text{Ra} < 10^{13}$$

The Raleigh number in these correlations was based on the respective height of each lump. In the vapor region this height was taken relative to the liquid level. Correlations in Equation 1 were modified to have scaling factors to account for the enclosure. These scaling factors were a function of liquid level and/or tank height, and vapor/liquid interface diameter.

Although the two dimensional flow dynamics of the boundary layer could not directly be incorporated into the one dimensional stratified tank model, it was incorporated in a one dimensional sense. Within each fluid lump the following boundary layer characteristics were determined:

- Characteristic velocity
- Boundary layer thickness
- Buoyancy driven volume flow rate

The characteristic velocity as well as the boundary layer thickness could be obtained by a general scaling analysis employing the use of Equation 1²:

$$\mathbf{2.a} \quad U \sim \alpha / H \text{ Ra}^{(2*0.2)}$$

$$\mathbf{2.b} \quad \delta \sim \text{Pr}^{(0.5)} (H \text{ Ra}^{(-0.2)})$$

The boundary layer was modelled as an energy exchange between the lumps using S/F FTIES. This energy was equivalent to the convective heat or, $\dot{m} C_p \Delta T$, of the boundary layer. These energy ties went only one way, "up", along the tank wall. Another set of S/F FTIES was employed to model the "mixing" of the flow. This mixing heat exchange between lumps was proportional to $\text{Ra}^{(0.33)}$ (Figure 3).

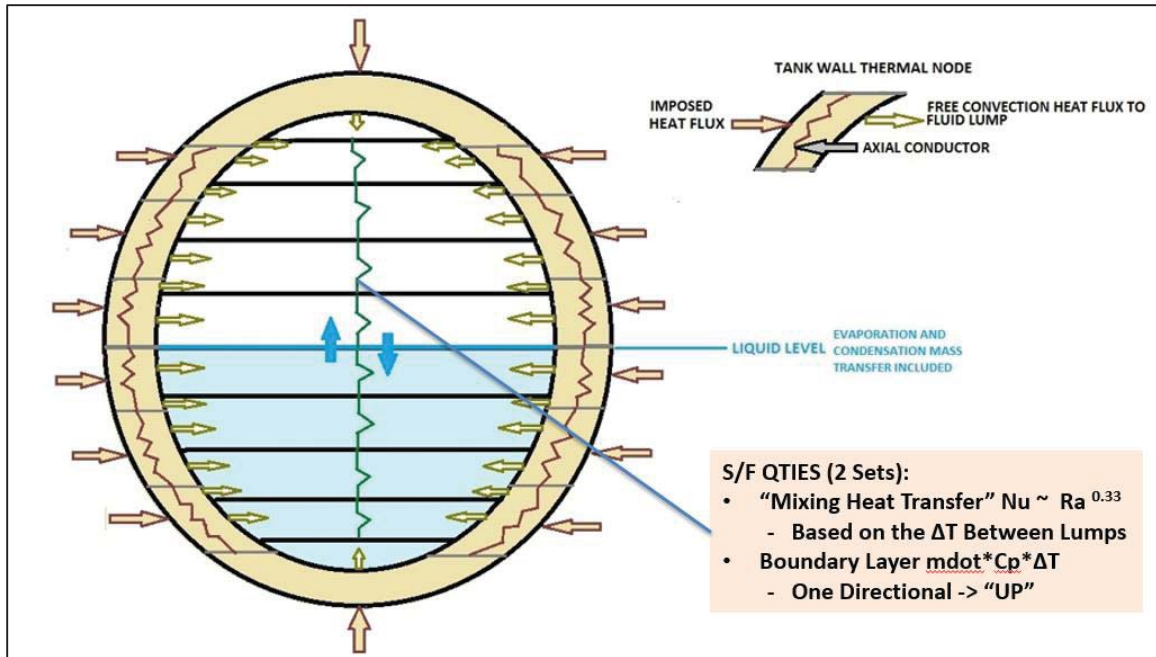


Figure 3: Stratified Tank Heat Transfer

SINDA/FLUINT Vapor Liquid Interface Modeling

SINDA/FLUINT contained pre-built utility functions to model heat and mass transfer between a liquid and vapor interface (TWIN TANKS). However to obtain modelling flexibility, user logic could incorporate the necessary physics to model a wide variety of scenarios. The vapor/liquid interface was modelled as a S/F PLENUM, or boundary state. There were actually two PLENUMS, one to represent the vapor and the other to represent the liquid. The saturation state of these PLENUMS was the saturated state of the "top" liquid lump and updated every iteration. A S/F FTIE was placed between the "bottom" vapor lump and the boundary PLENUM. Similarly a S/F FTIE was placed between the "top" liquid lump and the boundary PLENUM (Figure 4).

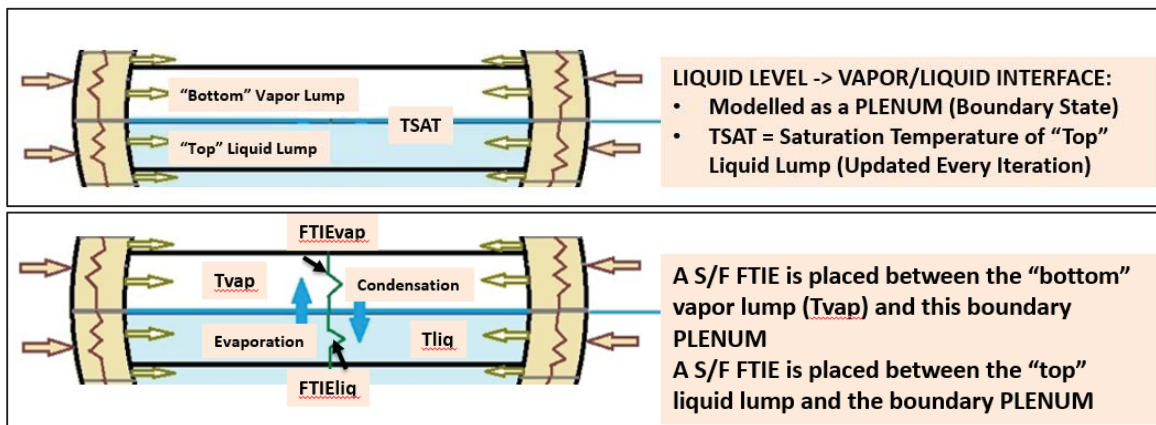


Figure 4: Interface Modelling

The heat rates for these FTIEs are defined as follows:

$$3a. \quad Q_{VAP} = h A_{INTER} (T_{VAP} - T_{INTER})$$

$$3b. \quad Q_{LIQ} = h A_{INTER} (T_{INTER} - T_{LIQ})$$

where,

$$4. \quad h = k Nu / D_{INTER}$$

$$5. \quad Nu \sim 0.04 Ra^{(1/3)}$$

Equation 5 was modified to have scaling factors to account for the enclosure. These scaling factors were a function of liquid level and/or tank height, and vapor/liquid interface diameter.

Evaporation was modeled via the process:

- Liquid leaves the “top” liquid lump and enters the interface PLENUM via a S/F MFRSET connector (Set Mass Flow Rate Connector)
- Vapor enters the “bottom” vapor lump from the vapor interface PLENUM via a S/F MFRSET connector

Condensation was modeled via the process:

- Vapor leaves the “bottom” vapor lump and enters the interface PLENUM via a S/F MFRSET connector
- Liquid enters the “top” liquid lump from the liquid interface PLENUM via a S/F MFRSET connector

The net evaporation rate at the interface is calculated to be:

$$6. \quad \dot{m}_{EVAP} = (Q_{VAP} - Q_{LIQ}) / (Hfg)$$

The mass flow rate, whether condensing or evaporating, should be at saturated conditions. However the “bottom” vapor and “top” liquid lumps may not be saturated. Thus when mass was removed from either of these lumps the amount of energy leaving these lumps needed to be adjusted to account for this discrepancy.

Model Case Input

In the Ksite model the heat load was applied uniformly through out the liquid and vapor regions. The results were compared to FLUENT CFD results and test data. Table 1 illustrates the relevant input parameters for the Ksite model³.

Fill Levels:	29%, 49%, 83%
Heat Rate:	3.5 W/m ² , 2.13W/m ²
Tank:	Oblate Spheroid Major Diameter = 87.6 in Minor Diameter = 73 in Volume = 4.89 m ³
Fluid:	Parahydrogen (Real Gas/Compressed Liquid)
Initial Conditions:	20.33 Deg K Saturated

Table 1: Ksite Input Parameters

SINDA/FLUENT Results

The results for the Ksite model are illustrated in the Appendix. For the Ksite case, 49% fill level, a sensitivity study was performed on varying the number of lumps in the vapor ullage and liquid region. For these runs the number of vapor wall nodes was 40, and the number of liquid wall nodes was 50. The other fill levels used as a “baseline” 40 lumps in the vapor ullage, 75 lumps in the liquid region, 40 vapor wall nodes, and 50 liquid wall nodes. For all three fill level at the 2.13 W/m², FLUENT CFD results were plotted as well as test data results.

Overall the results from the S/F stratified tank model compared well to test data and CFD results. The run time of the model with only one vapor lump and one liquid lump took less than 10 minutes of real time to complete. The “baseline” runs took approximately 1 to 2 hours of real time to complete. The run time seemed to be more dependent on the number of lumps in the liquid region since runs with 1 liquid lump and 80 vapor lumps took less than 1 hour.

APPENDIX

SECTION A: KSITE RESULTS

49% FILL LEVEL

3.5 W/m² , 2.13 W/m²

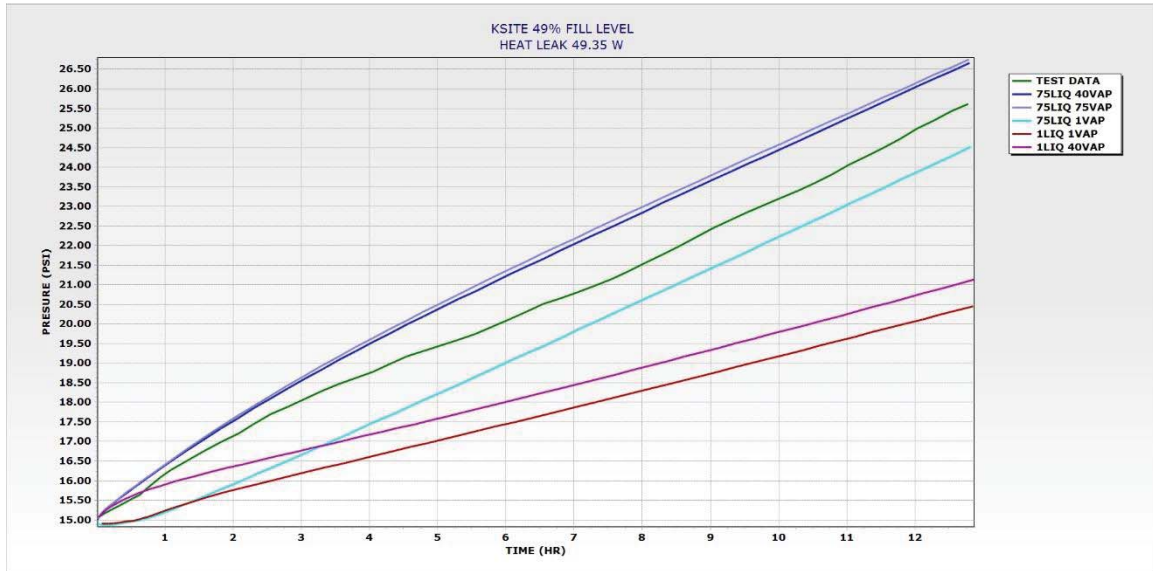


Figure A.1: Ksite 49%, 3.5 W/m²

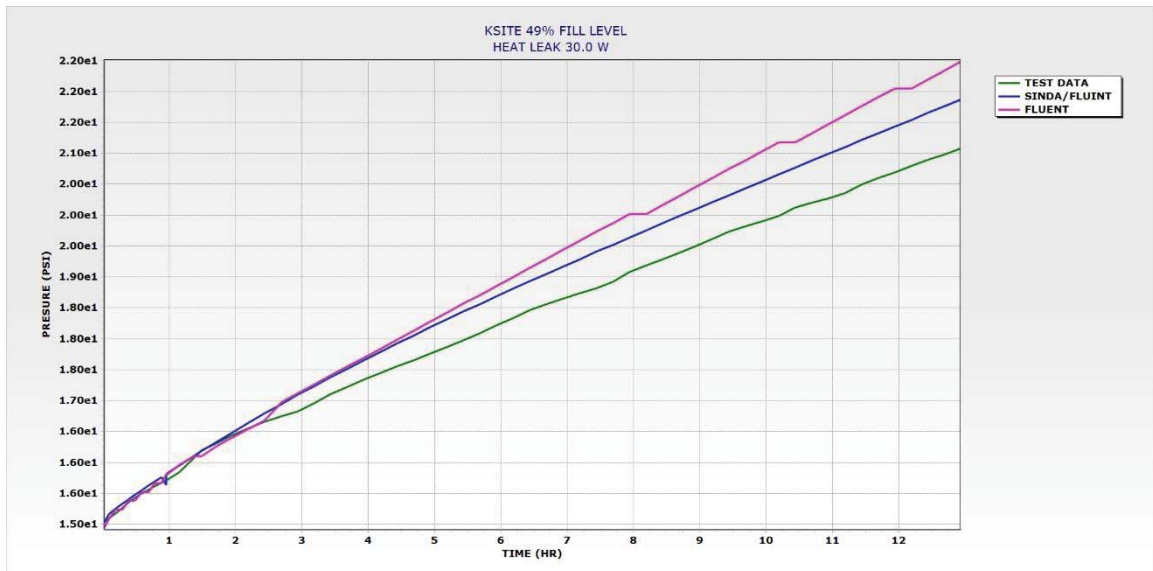


Figure A.2: Ksite 49%, 2.13 W/m², FLUENT

APPENDIX

SECTION B: KSITE RESULTS

83% FILL LEVEL

3.5 W/m² , 2.13 W/m²

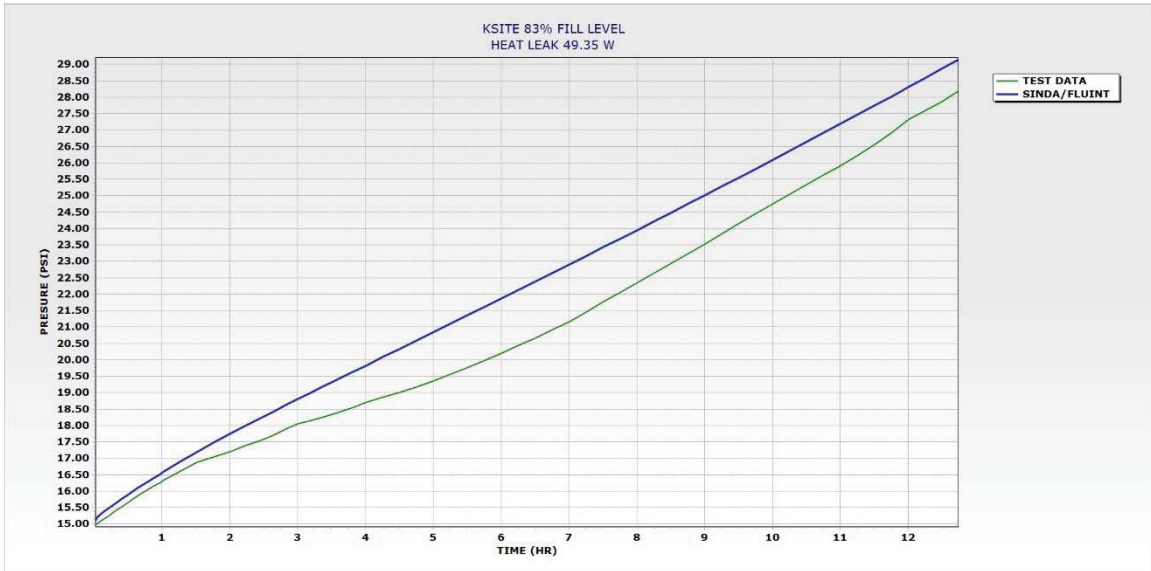


Figure B.2: Ksite 83%, 3.5 W/m²

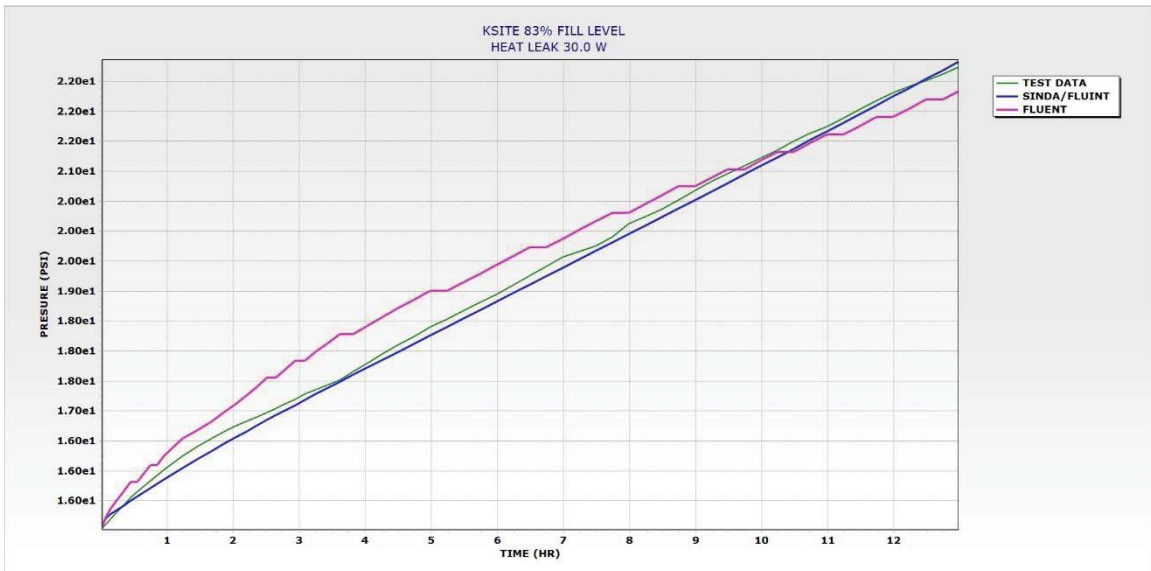


Figure B.2: Ksite 83%, 2.13 W/m², FLUENT

APPENDIX

SECTION C: KSITE RESULTS

29% FILL LEVEL

3.5 W/m² , 2.13 W/m²

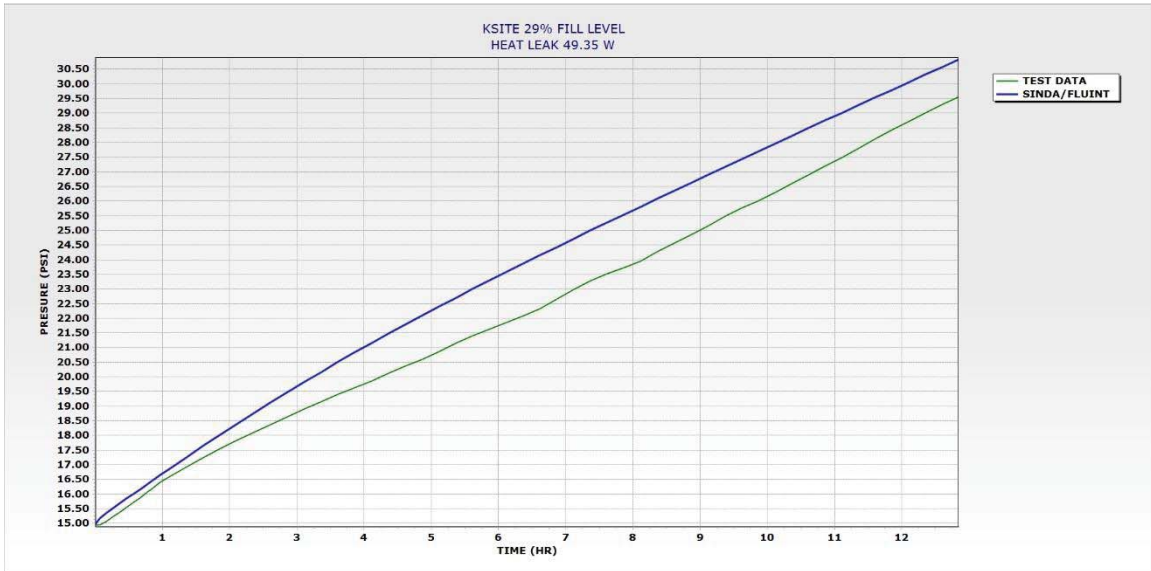


Figure C.1: Ksite 29%, 3.5 W/m²

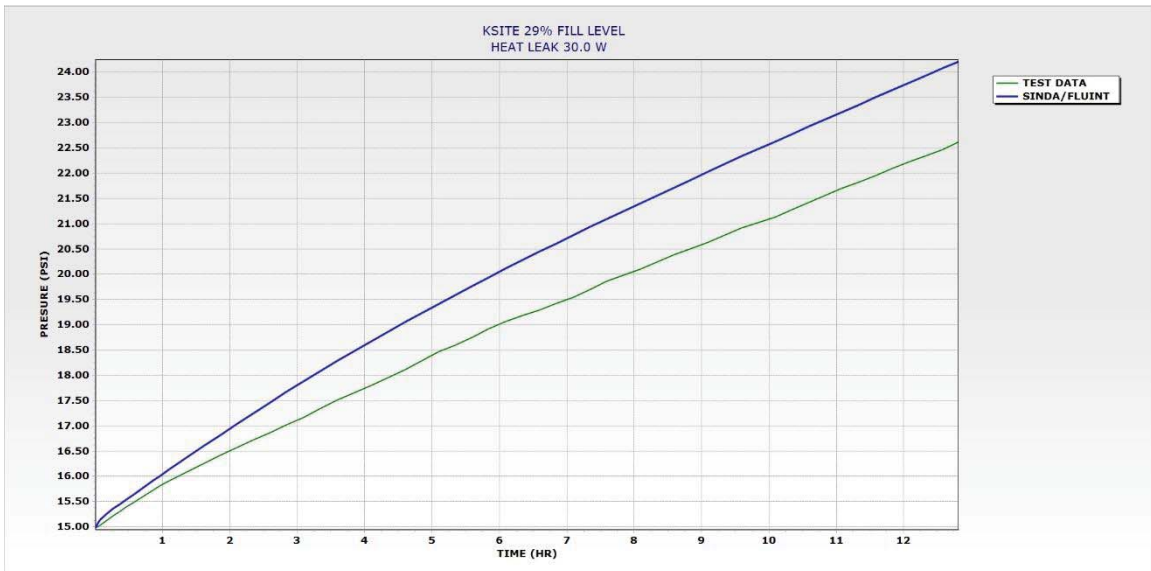


Figure C.2: Ksite 29%, 2.13 W/m², FLUENT

APPENDIX
NOMENCLATURE

α	Thermal Diffusivity
δ	Boundary Layer Thickness
ΔT	Temperature Difference
A	Area
C _p	Specific Heat
D	Diameter
h	Heat Transfer Coefficient
H	Height
H _{fg}	Heat of Vaporization
k	Thermal Conductivity
\dot{m}	Flow Rate
Nu	Nusselt Number
Pr	Prandtl Number
Q	Heat Rate
Ra	Raleigh Number
T	Temperature
T _{SAT}	Saturation Temperature
U	Velocity

SUBSCRIPTS

EVAP	Evaporation
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INTER

Interface Location

LIQ

Liquid

VAP

Vapor

REFERENCES

1. Bejan, Adrian, "Convective Heat Transfer", John Wiley & Sons Inc., 2004, pp 216.
2. Bejan, Adrian, "Convective Heat Transfer", John Wiley & Sons Inc., 2004, pp 188.
3. Hasa, M.M., Lin, C.S., and Van Dresar, N.T., "Self-Pressurization of a Flightweight Liquid Hydrogen Storage Tank Subjected to Low Heat Flux," 1991 ASME/AIChE National Heat Transfer Conference ,Minneapolis, Minnesota, July 28-31, 1991.