

An Excel User Interface for Modeling LHPs in SINDA/FLUINT

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ABSTRACT

Loop Heat Pipe (LHP) Technology has become an accepted technology for thermal management of spacecraft. Despite the acceptance of the technology, there remains a lack of understanding about how to analyze these devices, creating the myth that inadequate tools exist for modeling LHPs and CPLs (capillary pumped loops).

LHPs are two-phase devices with a very tight thermal coupling to their environment. Consequently these systems must be modeled in a manner capable of capturing both thermal and fluid behavior. Over the past decade various programs have been written to model LHPs and CPLs, however the majority of them have been either design-specific or focused on capturing a specific behavior within the system. SINDA/FLUINT is a thermal/fluid modeling code fully capable of capturing both heat transfer and fluid dynamics of an LHP. In addition it provides the flexibility to model any portion of the system in as much or as little detail as needed. Unfortunately, the perception that FLUINT is too difficult to learn has precluded many engineers and technologists from learning how to model LHPs.

A recently developed Application Programming Interface (API) provides a means of launching and controlling SINDA/FLUINT from a separate stand-alone software program. To support the analysis needs of engineers who are interested in evaluating LHPs and performing system level studies, but who do not have the resources required become fluent with SINDA/FLUINT, a Microsoft Excel-based front end has been developed using this API. The resulting LHP Launch Control Panel is a simple Excel-based user interface requiring no knowledge of SINDA/FLUINT nor any need to purchase licenses if no changes are required to the underlying model.

This paper will provide an overview of the LHP Launch Control Panel, discuss typical analysis results, and provide some guidelines on bracketing the LHP performance for stochastic phenomena such as evaporator core state. In addition it will provide

information for the advanced user on how to further customize the tool for their needs. The Excel-based LHP model is available in a licensed or unlicensed SINDA/FLUINT mode.

INTRODUCTION

Recent developments in the area of Application Programming Interfaces (APIs) provide a mechanism for integrating traditional thermal and fluid analysis software with higher-level design evaluation systems. The use of an API allows a thermal analysis tool such as SINDA/FLUINT to be launched as a subprocess from a separate stand-alone application such as MathWork's MATLAB® and Simulink®, Microsoft Excel®, Engineous' iSIGHT®, or Phoenix Integration's ModelCenter®, to create a multidisciplinary design environment customizable to the end user's specific needs. Using such an API with SINDA/FLUINT allows "Registers" and other data values to be passed back and forth between the applications, as commanded from either code. SINDA/FLUINT's dynamic mode allows the execution to be suspended and restarted to perform operations such as repeating a steady-state analysis, advancing a transient time step, or performing an optimization.

The LHP Launch Control Panel uses a COM-based API to integrate SINDA/FLUINT with Microsoft Excel; creating a simple Excel-based launch control panel for an underlying SINDA/FLUINT model of an LHP. The tool allows the user to launch predefined system-level steady-state or transient simulations. Additionally the user can launch a steady-state parametric analysis on heat load. The geometry of the LHP is passed from Excel to SINDA/FLUINT using registers which can be modified from the Excel interface.

The underlying LHP model is intended to represent the effects of the LHP at the system level: how the LHP affects the vehicle or payload. The model is sufficient to determine pressure drops in the system, to aid in line sizing and the evaluation of parasitic heating effects, and to provide bounding analyses. However the model is not intended for detailed LHP design problems such as

C&R TECHNOLOGIES
Loop Heat Pipe SINDA/FLUINT Run Controller

Version 1.01

Help

Enter the name of the Input File below (A12)
E:\LHPExcel\Nhp46excel.sin

Enter the name of the preprocessor output file below (A15)
pp.out

Loop Configuration

Compensation Chamber
Volume (m³): 1.12E-04

Evaporator
Length (m): 0.152
OD (m): 0.0254
Kwick (dry, W/mK): 45
pore radius (micron): 1.20E-06
permeability: 6.00E-01
Bounding core state: 1
1 = two phase
0 = superheated liquid

Heat Load (Watts):
Power (steady state):
(min for parametric)

Max Power (Transient): 500
(max for parametric)

Adverse tilt (degrees, non-negative): 90
Transport line wall conductivity (W/m-K): 15
Transport length (m): 1

Transport Section
Vapor Line ID (m): 0.0045
Liquid Line ID (m): 0.0045

Environment:
Tambient (K): 283
Tsink (K): 255
Gravity (m/s²): 9.8

Transport Line Convection:
 On Off Line H (W/m²-K): 10

Transport Line Radiation:
 On Off IR Emissivity: 0.1

Condenser
Condenser length (m): 3.8
Condenser wall conductivity (W/m-K): 200
Condenser ID (m): 0.0041
Overall conductance to sink (W/K): 30

Model Output

Name	Value	Units
Evap. Temp. (lines.T10)	0.0	K
Sat. Temp. (lines.t2)	0.0	K
CC Temp. (lines.T1)	0.0	K
Cond. Outlet Temp. (lines.T200)	0.0	K
Cond.Outlet XL (loop.XL200)	0.0	
Liquid return XL (loop.xl205)	0.0	
Capillary Limit	42800	Pa
Wick internal dP	3590	Pa
Total Pressure Drop	7690	Pa

How to use this LHP Run Controller:

Step 1: Using the BROWSE button to locate the input file (lhp46excel.sin). Do not edit the input deck unless you are familiar with SINDA/FLUINT usage.

Step 2: Click on the RUN SINDA/FLUINT button. A user text window will appear providing status dialog. All register values and output will be initialized.

Step 3: Select the type of solution and click SET INT REGISTERS.

Steady State
 Parametric
 Transient

Step 4: Update the parameters in loop the geometry, environment, and heat loads (red text). Send changes to SINDA/FLUINT by clicking the SET FLOAT REGISTERS button.

Step 5: Click the CONTINUE button to run the model. The model defaults to a steady state simulation. Upon completion, the MODEL OUTPUT parameters will be update automatically.

Step 6: The model repeats allows the user to continually modify registers and run the model (steps 3-5) until you click the KILL THE RUN button to terminate the run.

Customization: The advanced user can further customize the LHP Run Controller by accessing SINDA/FLUINT registers directory using the fields below.

Figure 1: Excel Based LHP Launch Control Panel

secondary wick optimization, capturing thermal gradients within the evaporator itself, or performing hydrodynamic start-up transient. These advanced modeling tasks would require extensive modification to the underlying input file as well as significantly more understanding of SINDA/FLUINT. Specifically, although this particular model is not intended for such advanced or specific applications, other SINDA/FLUINT models can be created for such purposes.

OVERVIEW

The LHP Launch Control Panel is a tool for launching and controlling SINDA/FLUINT simulations using an Excel control interface. The Excel interface is comprised of multiple worksheets: *SindaControl*, *PlotInfo*, *Parametric Plot*, *Transient Plot*, *AdvancedControl*, *Loop Network*, *Lines Network*, and *DataSetInfo*. These worksheets allow the user to modify, launch and postprocess results of the SIND/FLUINT model within an Excel environment.

The *SindaControl* worksheet is the main control panel and is depicted in Figure 1. This panel is divided into four areas: the input area, the loop configuration, the model output, and the usage instructions.

The Loop Configuration is where the user can define loop geometry, heat loads, environments, etc. These parameters have been defined using registers within

SINDA/FLUINT and can be changed without modifying the underlying input file.¹

The Model Output area contains SINDA/FLUINT “processor variables” as output, including important calculated values such as capillary limit and pressure drop. These values are updated automatically at the completion of a steady state or transient run.

The final area of the worksheet is the instructional area on the right. This area is used to launch, update, and stop the run the model using a series of control buttons strategically placed within the usage instructions. The LHP launcher allows the user to run a steady state simulation, a parametric sweep (series of steady state runs stepping through increasing power), or a single step power transient (stepping up in power from a minimum power steady state condition).

¹ The model assumes a single evaporator of circular cross-section with separate vapor and liquid transport lines to a condenser. The condenser is assumed to be a straight (non-serpentine) condenser.

USAGE AND CONTROL

After locating the input deck and defining the preprocessor output file name, the user launches the run by clicking on the “Run SINDA/FLUINT” button. This causes the API to launch SINDA/FLUINT. The underlying input file is already coded with the necessary logic to pause the API after entering the processor. A user text window will appear on the screen similar to Figure 2 letting the user know the status and for which type of input the program is waiting. At this time, the user selects the type of run (steady state, parametric or transient). To pass this information into SINDA/FLUINT, the user must click the “SetIntRegisters” button. The user then has the option of updating any parameters associated with loop geometry, power, or environments accessible through the LHP control panel. After updating these input parameters, the user must click the “SetFloatRegisters” button to pass the changes through the API to SINDA/FLUINT followed by the “Continue” button to release SINDA/FLUINT from the paused state and resume execution.

Upon completion, the SINDA/FLUINT run will update the Model Output area of the control panel with the new results. At this point SINDA/FLUINT is in a pause state and the user can plot data etc. as necessary to evaluate the results (as described next), or they may continue to modify input parameters and repeat the execution.

PLOTTING – For a steady state parametric or for transient simulations, predefined plot templates are provided for the user to evaluate the results. After running a parametric or transient, the user may access the *PlotInfo* worksheet (Figure 3) to refresh or modify the plot. This sheet provides access to the data set manager. The data set manager, shown in Figure 4, allows the user to modify which data is being plotted and how the plot is setup. The resulting plot of the baseline power parametric from 100 to 500 watts with an adverse tilt of 90° on the loop is shown in Figure 5.

WICK BACK CONDUCTION – The back conduction from the evaporator wall through the wick to the core is critical to predictions of loop conductance and therefore has been accounted for in the analyses. The conduction through the wick is treated as an effective solid using a standard radial conduction equation:

$$G = \frac{2\pi K_{eff} L}{\ln\left(\frac{R_o}{R_i}\right)}$$

where: L = thickness
 R_o = outer radius
 R_i = inner radius

For cylindrical wicks, the above term is corrected to account for the fact that the wick is wet and the temperature profile within the wick is not as simple as the



Figure 2: User Status Window

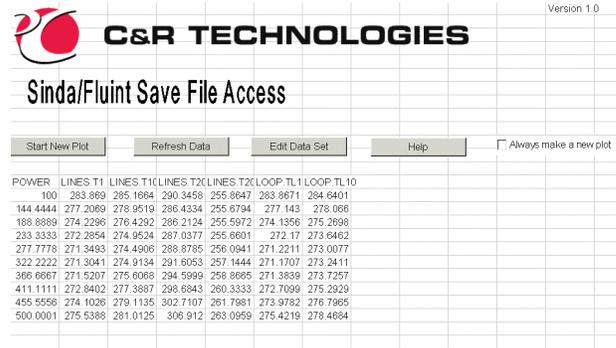


Figure 3: Plot Info Control

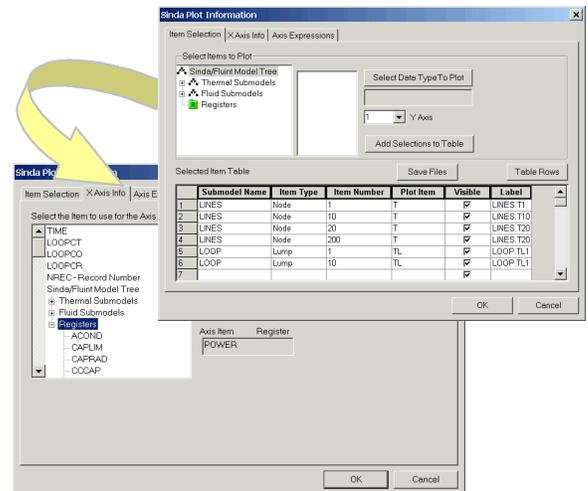


Figure 4: Data Set Manager

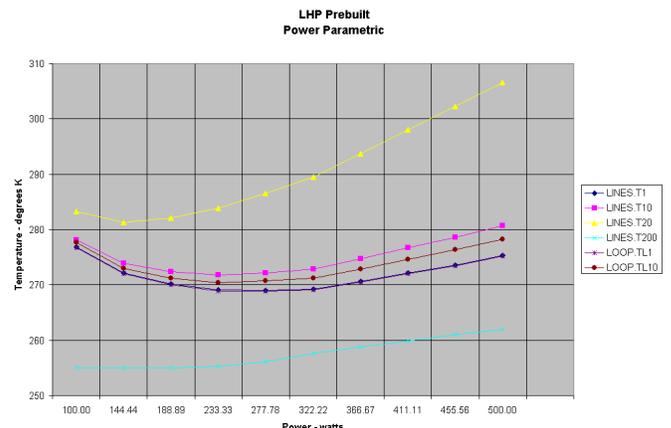


Figure 5: Power Parametric Results

above formulae imply. Rather, the influx of slightly subcooled liquid (relative to the saturation condition at the outer diameter of the wick) and the heat exchange of this fluid with the wick material results in a nonlinear profile. The correction for this heat exchange effect, which is normally rather small, is a function of the current flowrate (FR), liquid specific heat (Cp), etc. as shown below.

$$G_{corrected} = \frac{FR_{liq} \times Cp_{liq}}{\left(\frac{R_o}{R_i}\right)^{\left(\frac{FR_{liq} \times Cp_{liq}}{G_{uncorrected}}\right)} - 1}$$

The user can bound the effects of wick conduction by changing the value of the register WICKMETH in the *AdvancedControl* worksheet. This register sends a flag to the WETWICK subroutine in SINDA/FLUINT to select one of three options for calculating the wick back conduction. The options are:

- 1=parallel estimate
- 2=series estimate
- 3=sintered estimate

By default the effective conductivity through the wick is calculated using the Dunn and Reay correlation for sintered wicks.

$$K_{eff} = K_{wick} \times \left[\frac{2 + \gamma - 2\varepsilon(1 - \gamma)}{2 + \gamma + \varepsilon(1 - \gamma)} \right]$$

where: K_{wick} = thermal conductivity of the dry wick
 K_{liq} = thermal conductivity of liquid
 ε = wick porosity
 $\gamma = K_{liq} / K_{wick}$

EVAPORATOR CORE STATE – The operating temperature of an LHP is dependent on the phase of the fluid within the evaporator core (the low pressure side of the wick), especially at low powers. Based on the liquid/vapor state in the core, the heat leak between the evaporator and the compensation chamber changes as does the “back conduction” of heat from the high pressure side to the low pressure side of the wick.

If vapor penetrates the wick during startup, or if the core fluid nucleates, then two-phase fluid can be expected in the core, and can be maintained there indefinitely. One effect of a two-phase core is higher heat transfer coefficients from the inside surface of the wick to the core, increasing the back conduction term which must be offset by increased subcooling (and therefore increased “blockage” of the condenser). In other words, while most liquid is vaporized on the higher pressure side of the wick, some can be vaporized on the lower pressure side as well, representing a degradation in overall loop conductance analogous to leakage flow in a mechanical pump. Vapor generated within the core can be condensed by contact with colder bayonets or by

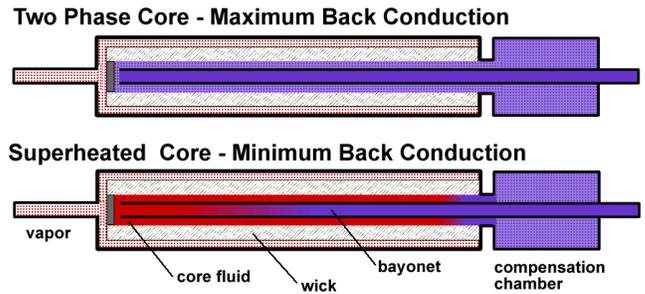


Figure 6: Bounding Core States

transport to the compensation chamber (via percolation or even via heat pipe action), but in any case this condensation must be “purchased” at the expense of increasing the subcooling.

A two-phase or nearly vapor-filled core (upper portion of Figure 6) therefore represents a maximum conductance on the inside surface of the wick, and therefore is the upper limit for back conduction and the lower limit for loop conductance. The opposite bounding case is a superheated (metastable) liquid core (shown in the lower portion of Figure 6), which results in negligible back conduction and therefore maximum loop conductance.

Typically the performance of the loop will fall somewhere between these two extremes at low power, perhaps as a function of void fraction within the core. The core state has less effect on the operation of the loop at higher powers.

Due to the stochastic nature of nucleation (conversion of the superheated core to a two-phase core), and due to the current inability to predict how much liquid or vapor will reside in the core (nor how the back conduction will be affected even if such a prediction were possible), the user must bound the LHP performance based on the limits of possible states. If the core is nearly empty of liquid, the LHP will achieve its lowest conductance (important for sizing radiators, for example). If the core maintains a superheated liquid state, the LHP will achieve its highest conductance (important for sizing make-up heaters, for example). As with any uncertainty in engineering, designing conservatively for the extremes is necessary, making predictions of the exact state of the core desirable in the future, but somewhat academic in the present.

A core phase multiplier has therefore been defined on the worksheet *SindaControl* to provide the user to a simple means to bound the core state between the maximum and zero wick back conduction. Quite often, a wick back conduction much higher than theoretical is observed in an LHP. Although the explanation of this increased back conduction currently eludes technologists, such performance can be simulated by setting the core phase multiplier to values greater than 1 for an augmented two-phase core.

LHP Prebuilt
Core State Bounding Analysis

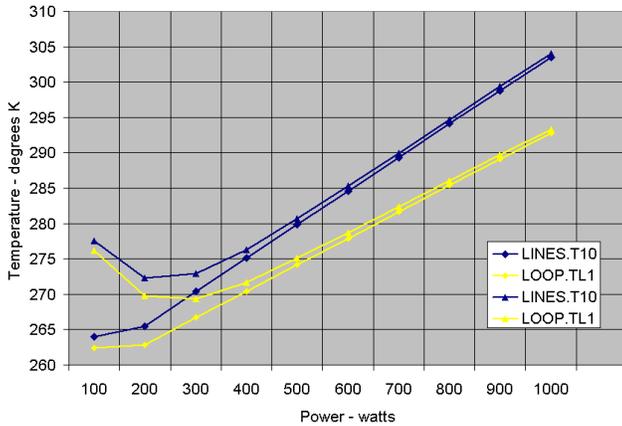


Figure 7: Core Bounding Analysis

Core Multiplier Values

- 0 = superheated core
- 1 = two-phase core
- >1 = augmented two-phase core

Figure 7 depicts the results of a typical bounding analysis between a superheated core and a two-phase core. The diamond shape represents a two-phase core and the triangle represents a superheated liquid core. The temperature LINES.T10 represents the evaporator body while the temperature LOOP.TL1 represents the liquid saturation temperature.

ADVANCED OPTIONS – There are two levels of modifications available to the user. First, the user has the ability to modify simple parameters beyond those defined on the *SindaControl* worksheet without requiring proficiency in SINDA/FLUINT. Such basic modifications include items listed in Figure 8 such as the how the wick back conduction calculated, thermal conductance between the evaporator and compensation chamber, or working fluid, just to highlight a few. These parameters are accessible from the worksheet titled *AdvancedControl*. If the user modifies these values, the SetIntRegisters and/or SetFloatRegisters on the *SindaControl* worksheet must be clicked to propagate the changes.

Secondly, if the user is proficient with SINDA/FLUINT and has a license, the underlying input file can be modified. Such modifications may include detail in the evaporator to capture thermal or fluid gradients within the evaporator, parallel condensers, or expanded detail within the condenser and associated radiator to fully characterize subcooling requirements etc.

For the advanced user needing to modify the underlying input file, the worksheets *Loop Network* and *Lines Network* provide R-C network diagrams of the fluid and thermal models respectively. These network diagrams are shown in Figure 9.

Integers Registers			
Click SET INT REGISTERS to send changes to Sinda/FLUINT			
Description	Name	Current Va	New Value
Fluid ID number 717 - ammonia 718	FLUID	717	
Method to estimate wet wick conduc	WICKMETH	3	
Number of steps in parametric . MUS	PSTEPS	10	
Wick conductivity (CONWCK) flag. s	CWET	0	

Floating Point Registers			
Click SET FLOAT REGISTERS to send changes to Sinda/FLUINT			
Description	Name	Current Va	New Value
Thermal Capacitances			
Radiator heat capacity (W/C)	CAPRAD	7215	
CC thermal capacitance (W/C)	CCCAP	866.70001	
Payload thermal capacitance attach	PLCAP	4815	
Evaporator thermal capacitance (W	EVPCAP	649.53601	
Vapor line specific heat *density	VAPCPD	3588000	
Liquid line specific heat *density	LIQCPD	3588000	
Miscellaneous Parameters			
Endtime for transient simulation, sec	ENDTIME	1800	
Width of evaporator mount (m)	EVPWIDE	0.0254	
Conductance from compensation ch	GAMBCC	0.045	
Conductance from evaporator to cor	GEVPC	0.053	
Hydraulic diameter of evaporator gro	GRVDH	0.0012	
Number of axial grooves in the evap	GRVNUM	6	
2 x wall thickness of the liquid line	THKLIQ	0.0009	
2 x wall thickness of the vapor line	THKVAP	0.0009	
Evaporator internal heat transfer co	UEVAP	11000	
volume of vapor tank (m3)	VAPVOL	4.169E-05	
Liquid fraction at which compensati	CCDRY	0.3	
Liquid fraction at which compensati	CCFULL	1	
additional K-factor loss in condense	FKCOND	0.1	
degradation of UEVAP at maximum	UDEG	0.25	

Figure 8: Advance Control Options

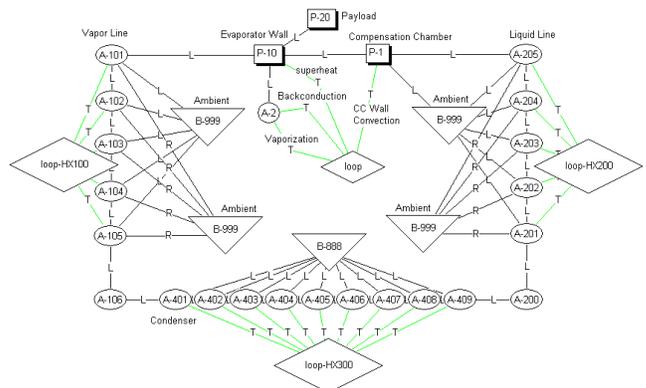
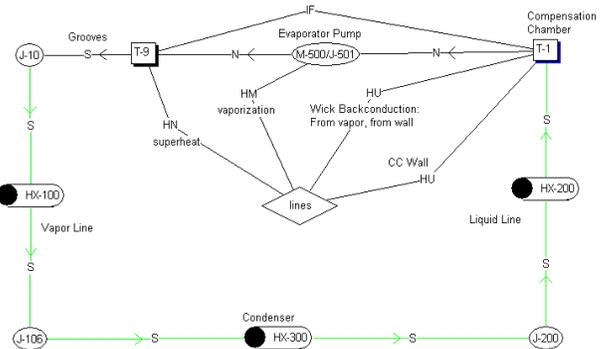


Figure 9: Submodel Network Diagrams

CONCLUSION

In summary the Excel LHP Model Launcher provides a simple to use front end for controlling and launching a SINDA/FLUINT model of a loop heat pipe. Its basic usage requires no understanding of the complexities within the underlying SINDA/FLUINT model. Consequently, it provides any user, regardless of technical background, a basic tool to assess and evaluate the performance of a loop heat pipe.

Advanced SINDA/FLUINT users can use the Excel API to develop and customize similar control panels for any SINDA/FLUINT model. Options are available to run such models in a license or unlicensed mode.

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