

How to Model a Heat Pipe

A brief explanation is provided of a network-based method that is suitable for modeling constant conductance heat pipes (CCHPs, also called fixed conductance heat pipes or FCHPs) and vapor chamber fins. This method has been used in the aerospace industry for about three decades for supporting system-level design analysis.

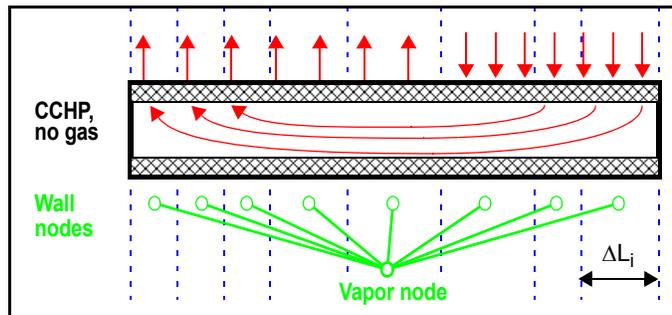
Extensions of these methods are available for modeling CCHPs degraded by noncondensable gas (NCG) generation, or variable conductance heat pipes (VCHPs) with NCG reservoirs introduced to provide temperature control. Extensions are also possible for modeling planar or counterflow thermosyphons, but this method is cannot be extended to loop thermosyphons (LTSs). Similarly, methods for modeling loop heat pipes (LHPs) are distinct.

How Not to Model a Heat Pipe

A common “trick” is to model a heat pipe as a bar of highly conductive material. However, that method (1) does not simulate a heat pipe’s length-independent resistance, (2) cannot account for differences in film coefficients between vaporization and condensation, (3) can be disruptive to numerical solutions, (4) does not provide information on power-length product (QL_{eff} , for comparison against vendor-supplied heat pipe capacity), and (5) cannot be extended to include NCG effects. Another misconception is that heat pipes, being two-phase capillary devices, require detailed two-phase thermohydraulic solutions. While codes capable of such details exist, such as C&R’s SINDA/FLUINT, such an approach would represent computational overkill in almost all cases: even heat pipe vendors use simpler calculations when designing heat pipes.

Basic 1D (Axial) Model

A diagram of a CCHP (black) plus a network-based model (green) is shown at the right. (Possible heat flows are shown in red, but actual heat flows may differ.) The key to this approach is the use of a single node in the middle, the vapor node, to which all wall nodes attach directly via a “fan” of linear conductances or resistances. This massless vapor node (“arithmetic” in SINDA parlance) corresponds to the saturation condition in the pipe.



Strictly, the “wall nodes” represent the liquid/vapor interface along each (i^{th}) axial segment of length ΔL_i . Separate nodes could be used to subdivide the pipe wall and wick radially, but often such gradients are neglected: the wall nodes represent the entire section of pipe. These wall nodes may have zero or finite thermal capacitance. They can be interconnected axially, if desired, to represent the thermal conductivity of the wall and wick. For a pipe whose cross section has perimeter P at the liquid/vapor interface, the wall nodes are connected to the vapor node by a resistance:

$$R_i = 1/G_i = 1/(H_i P \Delta L_i)$$

where H_i is equal to the evaporation film coefficient if $T_i > T_{vapor}$, or the condensation coefficient if $T_i < T_{vapor}$. These coefficients can differ from each other by up to a factor of two in some designs.

The power-length product, QL_{eff} , measures how far the pipe is from its rated capacity at the current temperature, as determined by the internal limits (wicking, boiling, entrainment, sonic, or viscosity). Since such data ($QL_{eff,max}$ versus temperature and tilt) should be available from the vendor, there is no need to check these limits explicitly. Assuming the radial heat flow through each segment is Q_i , the QL_{eff} product may be calculated by integration from one end of the pipe to the other, returning the maximum absolute power-length product encountered:

$$QL_{eff} = \max_i | [\sum_i (Q_i/2 + \sum_{j=0,i-1} Q_j) \Delta L_i] |$$

Axial and Circumferential, and Other 2D Models

The above 1D finite difference model implicitly assumes that the heat pipe is isothermal around its circumference. This assumption cannot be made in many cases, such as an evaporator bonded to only one side of a plate. Fortunately, the above methods are easily extended to 2D cases. In a finite difference cylindrical 2D grid, all wall nodes still connect to the same vapor node with resistances inversely proportional to their heat transfer area. (The QL product concept can be strained, however, if strong circumferential gradients are stronger than axial gradients.) There is similarly no requirement for use of finite differences: the pipe can be modeled with finite elements as well.

