Thermodynamic Optimization of Heat/Cold Sink Extenders in Thermoelectric Cooling Assemblies

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INTRODUCTION

The heat sink extender (HSE) is normally conceived of as a thermally conductive block which is mounted to a heat sink. The thermoelectric (TE) module is then, in turn, mounted on top of the HSE. Typically, the footprint of the HSE matches the footprint of the TE module. Figure 1 shows a sketch of a TE system in which an HSE is used.

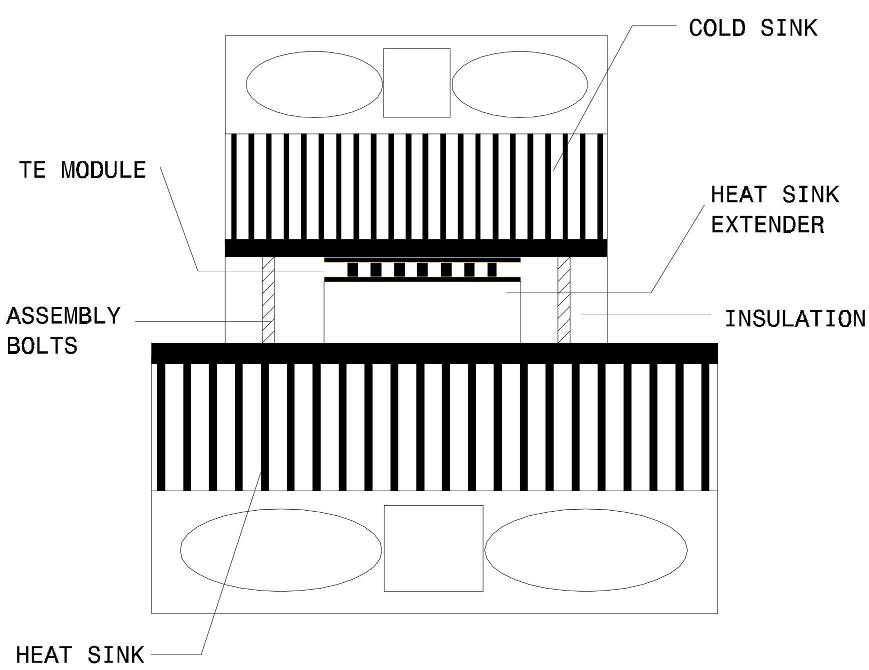

FIGURE 1. Typical thermoelectric system using a heat sink extender.

The cold sink extender (CSE) is much like an HSE. However in this case, the TE module mounts directly to the heat sink. The CSE then mounts to the top of the TE module. Figure 2 shows a sketch of a TE system in which a CSE is used.

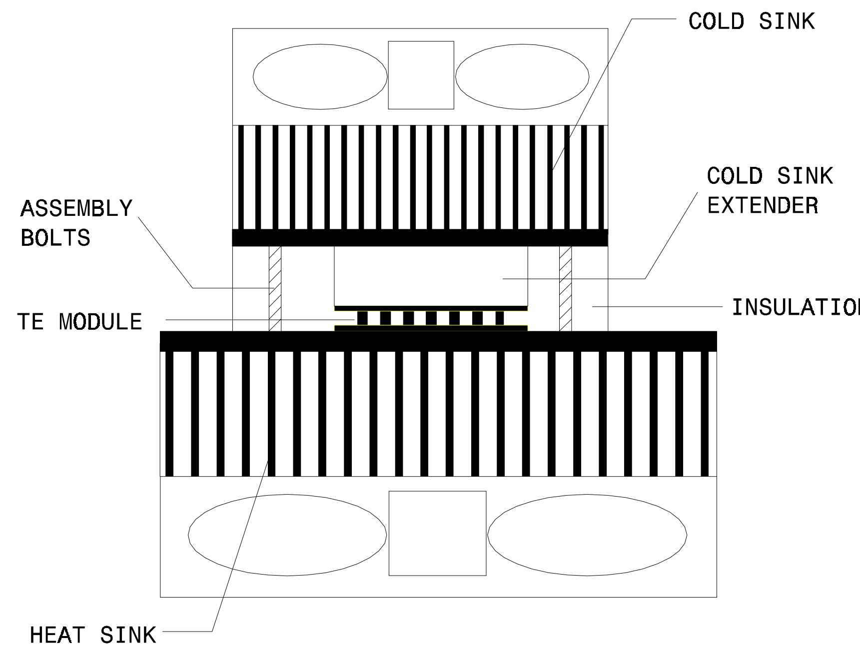

FIGURE 2. Typical thermoelectric system using a cold sink extender.

The use of an extender can serve several purposes. One purpose is to increase the distance from the heat sink plate to the cold sink plate. This allows for thicker insulation and longer assembly bolts. As a result, heat conducting from the heat sink plate back to the cold sink plate is reduced. It is hoped that this will then improve the coefficient of performance.

Another purpose involves temperature control. In certain control schemes, the TE system operates until a thermostat trips off. With an HSE or CSE in use, there is a larger thermal resistance present between the heat sink and cold sink. As a result, the cold space does not heat back up as quickly as with systems that do not employ HSE's or CSE's.

Probably the most important use of an extender, is when the extender serves as a thermal junction. In many applications, a TE system is used to cool an insulated box. The cold sink and heat sink are separated by the thickness of the box's insulation. The extender, therefore, is used to thermally join the TE module to either the cold sink or the heat sink. Extenders have been used in this fashion in picnic cooler boxes seen on the commercial market. However, some TE systems are using an HSE while others are using a CSE. Which is better to use? This paper will address that question with specific answers as well with some general guidelines.

THEORETICAL BASIS

The use of HSE's or CSE's does decrease the plate-to-plate thermal conductance. However, a HSE will increase the heat sink's resistance to heat transfer. Consequently, the TE module will run at a higher hot-side temperature. In effect, the TE module will operate at a larger temperature differential than for a non-HSE system. Similarly, the CSE increases the cold sink's resistance to heat transfer. As a result, the TE module will have to operate at a lower cold side temperature than for a non-CSE system. There exists, therefore, an optimum extender design derived from the balance between the reduction in the plate-to-plate thermal conductance and the TE module's operation at a larger temperature differential.

The basis for the optimization of the extender is the minimization of the generation of entropy. In effect, the design that uses an optimized extender will need less power to achieve a given set of heat pumping conditions than designs using non-optimized extenders. It will be seen, however, that in some instances it is best to use no extender at all.

The nature of the effort to minimize the entropy generation can be seen by examining the following equation. The operating entropy generation $(\dot{S}gen)$ equation is as follows:

$$\dot{S}gen \;=\; \frac{dS}{dt} - \sum_{i=0}^{n}\frac{\dot{Q}_i}{T_i} - \sum_{in}\dot{m}s + \sum_{out}\dot{m}s \geq 0 \qquad (1)$$

Certain assumptions are made regarding the use of extenders in modeling a TE system:

- The system is at steady state. Hence, $\frac{dS}{dt}$, the rate of entropy accumulation is zero.

- Heat transfer through an extender occurs solely from the extender-sink interface to the extender-TE module interface.

- The heat and cold sink plates are isothermal.

- The extender footprint matches the TE module footprint.

Equation (1) can be applied to the particular extender as seen in Figures 3 and 4. Equation (1) then reduces to the following by substituting $\dot{Q} = \frac{kA}{L}(T_{higher} - T_{lower})$:

$$\dot{S}gen\Big|_{CSE} = \frac{\left(\dot{Q}_{EXT} + \dot{Q}_{hot-cold}\right)^2}{k\frac{A}{L}T_{cold}T'_{cold}} \qquad (2)$$

$$\dot{S}gen\Big|_{HSE} = \frac{\left(\dot{Q}_{power} + \dot{Q}_{EXT} + \dot{Q}_{hot-cold}\right)^2}{k\frac{A}{L}T_{hot}T'_{hot}} \qquad (3)$$

where, referring to the extender, k is the thermal conductivity
A is the cross-sectional area
L is the extender length

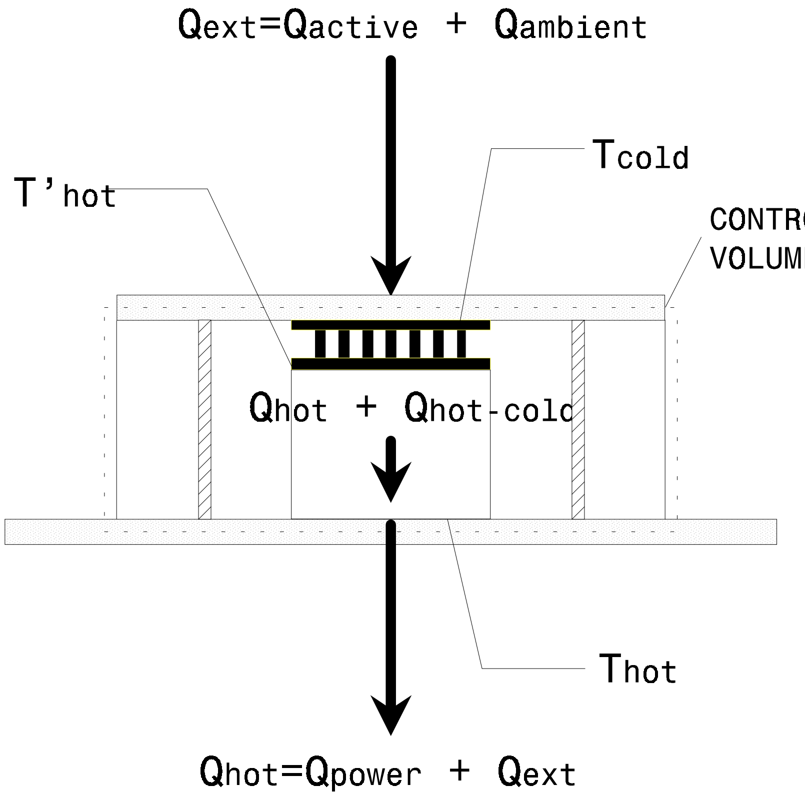

FIGURE 3. Heat flow through heat sink extender system.

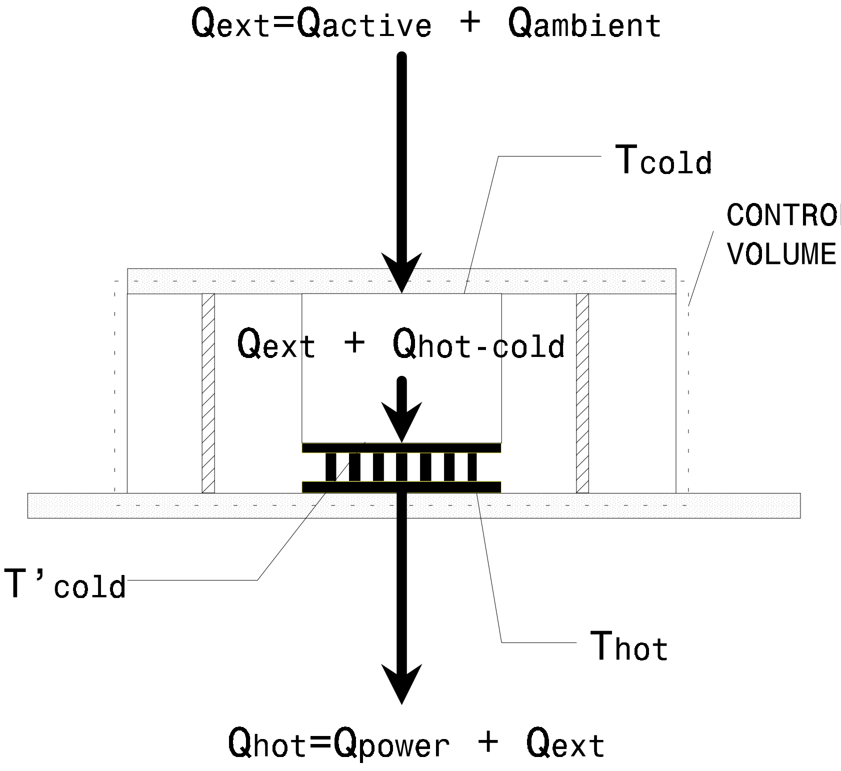

FIGURE 4. Heat flow through cold sink extender system.

However, equations (2) and (3) are not readily amenable to analytical expressions that indicate whether it is better to use an HSE or CSE. A general comment can be made regarding extender use though. It is seen from comparing equations (2) and (3) that $\dot{S}gen\big|_{HSE}$ is likely to be greater since the numerator in equation (3) will be greater than the numerator of equation (2). Furthermore, presuming the same physical parameters for the HSE as for the CSE, $\left(T_{hot}T'_{hot}\right)/\left(T_{cold}T'_{cold}\right)$ will be approximately unity for typical systems. To verify this, a detailed computer model was set up to analyze any given TE system using HSE's, CSE's, or no extenders at all.

CASE STUDY

There are many TE systems and many heat pumping conditions that these systems may operate at. However, the picnic cooler boxes mentioned in the introduction are of commercial importance. This case study, much as in the picnic cooler boxes, will examine an air-to-air exchanger that pumps 15W of heat to maintain a 5°C cold space in a 27°C ambient. The system uses one TE module having 127 couples of 0.055 inches wide by 0.045 inches tall sized pellets with a figure of merit = 2.5 (1000/°C) at 27°C. The heat sink design was held constant. The cold sink design, on the other hand, was varied in its footprint: 2.4, 3.2, 3.6, and 4.8 inches square. These dimensions were chosen for their correspondence with the standard dimensions of cooling fans. The larger footprint effectively decreases the cold sink's resistance to heat transfer so that the TE module can operate at a higher cold temperature. However, the larger footprint also presents more surface area for heat to transfer from the heat sink back to the cold sink. In brief, the TE system is parametrically modeled at increasing HSE heights for each cold sink. The same is done for increasing CSE heights.

RESULTS

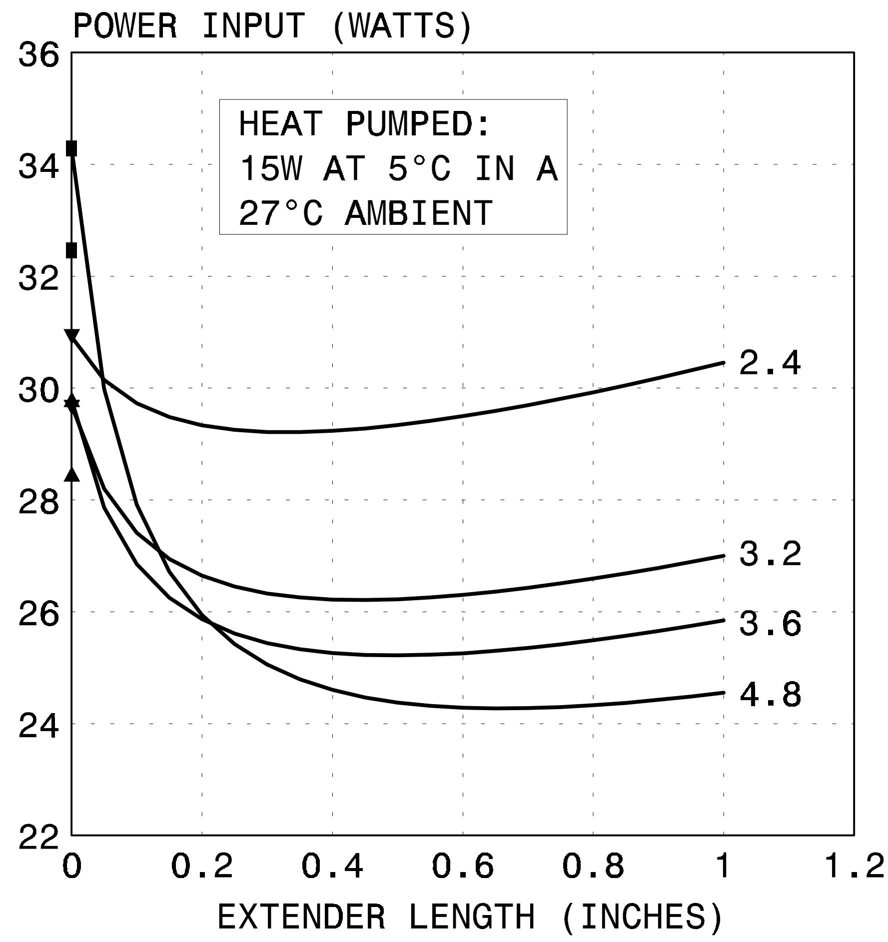

FIGURE 5. Power input versus heat sink extender length.

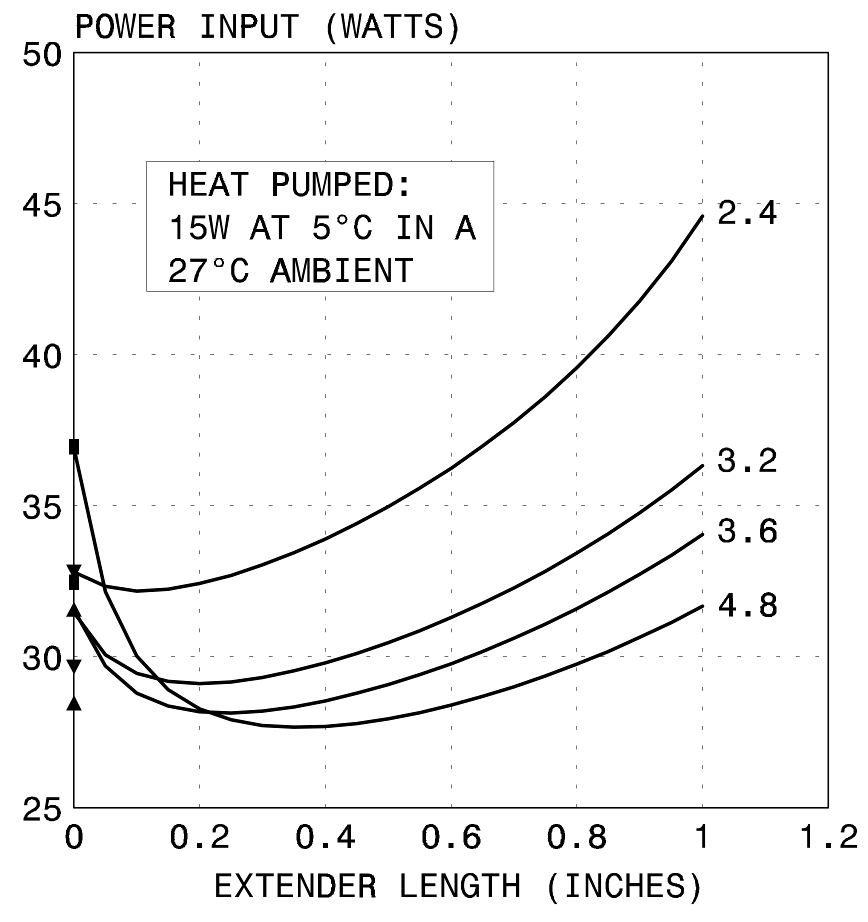

FIGURE 6. Power input versus cold sink extender length.

Figure 5 shows the required input power versus the HSE height, and Figure 6 shows the input power versus the CSE height. Each curve shows the performance when a particularly sized cold sink was used. The number associated with each curve indicates the square dimensions (in inches) of the cold sink plate. It should be noted that there are two marked points on the zero extender-length line for each curve. The lower point corresponded to a system with only one thermal interface between the TE module and the sink. The upper point, which begins the trace of a given curve, corresponded to an infinitely small extender length with thermal interfaces on each side of the extender. The analysis assumed that the interface was a silicon-based thermal grease joint. This grease joint had a 0.03°C/W thermal resistance for a 40mm by 40mm sized TE module. In some systems, however, the extender can be machined directly into the sink plate thereby eliminating the extra thermal resistance.

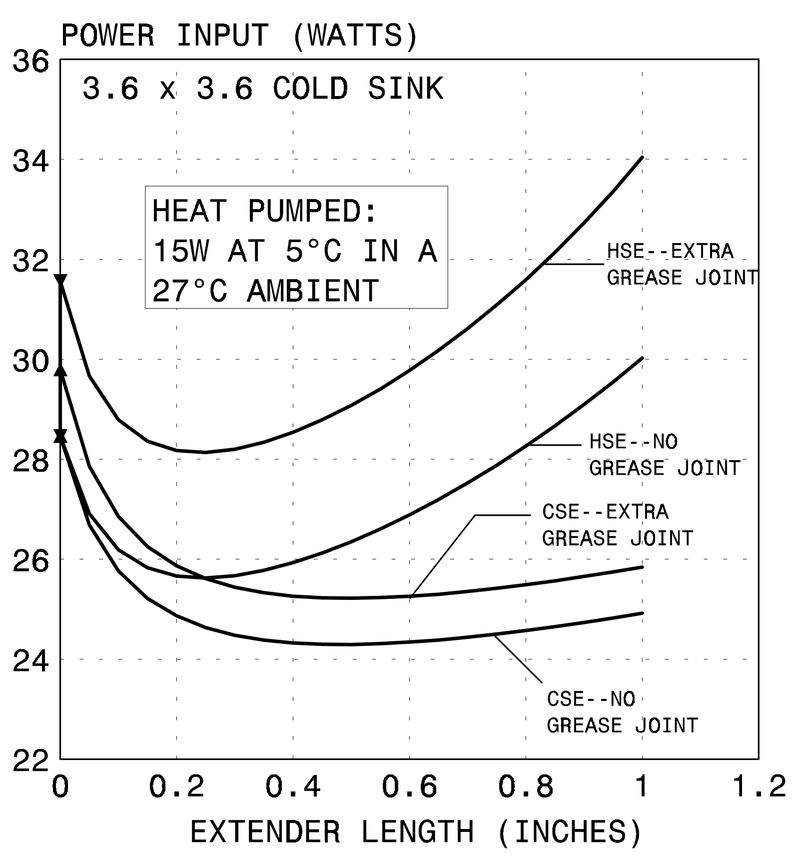

FIGURE 7. Power input versus extender length.

Figure 7 shows the cases where extenders were machined into the plate versus the attachment of the extender by the use of a grease joint. The extra grease joint did raise the power input requirement over the case where the extender was machined in. However, the extra grease joint did not affect where the optimum extender length occurred.

Referring back to Figures 5 and 6, an interesting observation can be made for the no-extender case: There existed an optimally sized cold sink footprint. In other words, a larger cold sink, with its reduced resistance to heat transfer, did not always improve performance. Without the use of an extender, the advantage of operating the TE module at a higher cold side temperature can be overcome by the increase in plate-to-plate losses (an increase in heat transfer from the heat sink back to the cold sink).

Figure 5 shows that the 4.8 cold sink paid off with the use of a 0.35 inch tall HSE. The 3.6 case marginally had an optimum HSE length, but the 2.4 and the 3.2 cases showed no improvement whatsoever when an extender was used.

Figure 6 shows that regardless of the cold sink footprint, there existed an optimum CSE length. The 4.8 case showed an especially dramatic improvement: at the zero CSE length the required power input was 32 W. At 0.65 inch CSE length, the power input was reduced to 24W.

However, Figure 8 shows that an optimum extender length does not always exist. For this heat pumping condition, it was best not to use any extender at all. Less power was required, though, when comparing the CSE-system to the HSE-system.

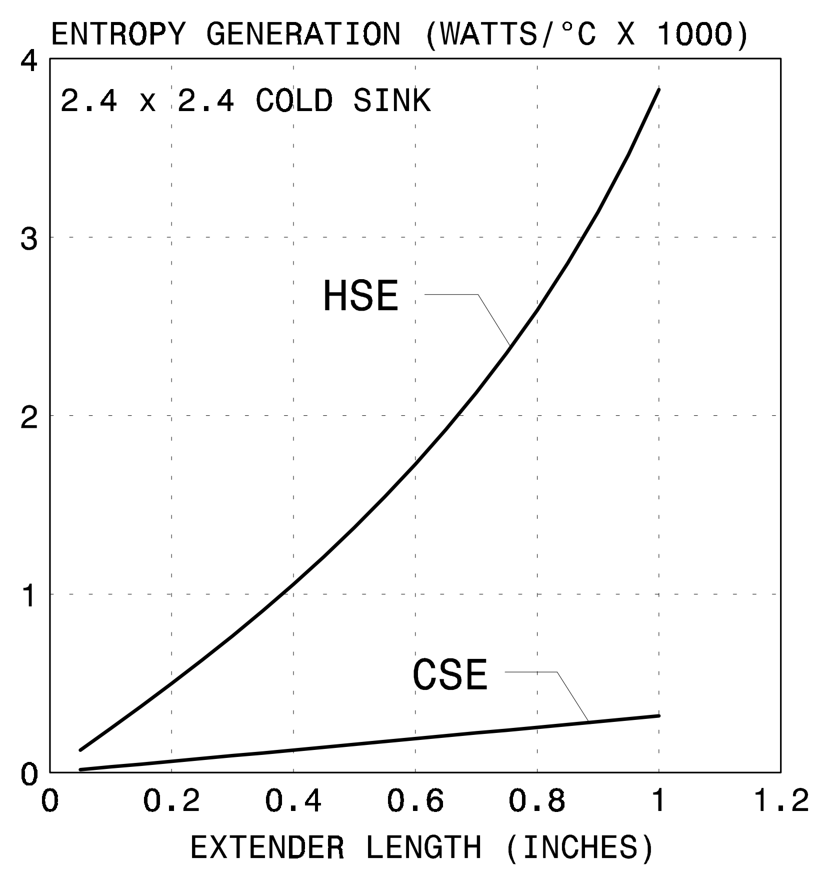

FIGURE 8. Power input versus extender length.

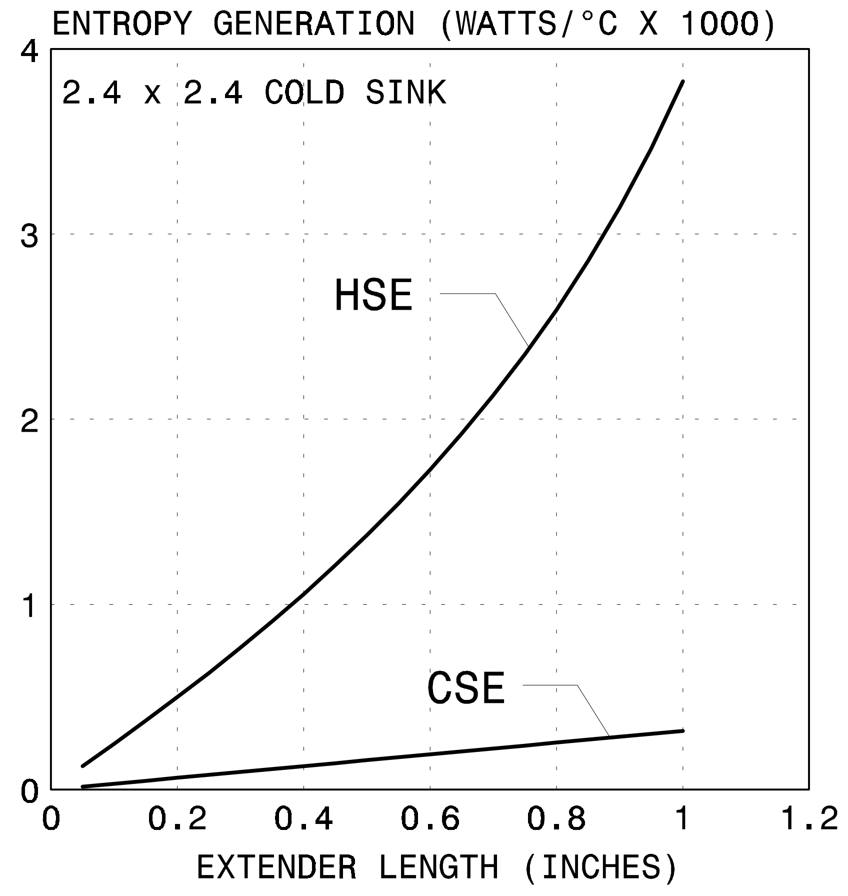

FIGURE 9. Entropy generated by extender.

The basis for CSE-system giving better performance than HSE-system is seen in Figure 9. Figure 9 shows the entropy generated by the CSE and by the HSE when the 2.4 cold sink was used. These curves are also representative of the extenders using the 3.2, 3.6 and 4.8 cold sink. Clearly, the HSE generated more entropy than did the CSE. A CSE-system would, therefore, have a higher Second Law efficiency than would a HSE-system.

CONCLUSIONS

In general, it is best to use CSE's rather than HSE's. Specifically, though, any given heat pumping condition needs to be evaluated on a case-by-case basis to determine if an optimum extender length exists or if an extender should be used at all. This evaluation can be especially important when the cold sink footprint is large in comparison to the TE module footprint. For example, in Figures 5 and 6, the use of an extender in the 4.8 cold sink case yielded significant reductions in the required power input as compared to the zero-extender length case. In other words, it becomes increasingly important to use an extender as the cold sink footprint increases in size. For some cases, though, as seen in Figure 8, it is better not to use any extender at all.

Finally , a CSE, as seen in Figure 9, generates less entropy than an equivalent HSE. Figure 9, while application specific, is indicative of most cases. Therefore, it can not be emphasized enough, use a CSE if an extender is necessary for service as a thermal junction.

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