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Heat rate investigation in parallelogrammic air-filled enclosures

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1. Problem definition

This study is about the thermal insulation benefits of using parallelogrammic air-filled enclosures in walls as well as on its material saving potential. Polystyrene panels made with a stack of enclosures were studied with numerical simulations. The geometry and the parameters considered are shown on the figure. The proposed wall is assumed to be thermally insulated at its ends. To simplify the calculations, a single enclosure is considered with periodic conditions. This domain is much smaller and allows the numerical cost to be reduced considerably. The cavity angle is set to 60° because at this angle, the effect of stratification, which should help in reducing convection heat transfer, is expected to be significant while the structural stiffness of the wall should remain acceptable.

The analysis of the insulation capability was carried out by reporting the heat rate through the wall, which is expressed as a Nusselt number. Moreover, to consider both the insulation efficiency and the material saving potential, the efficiency parameter ξ is used.

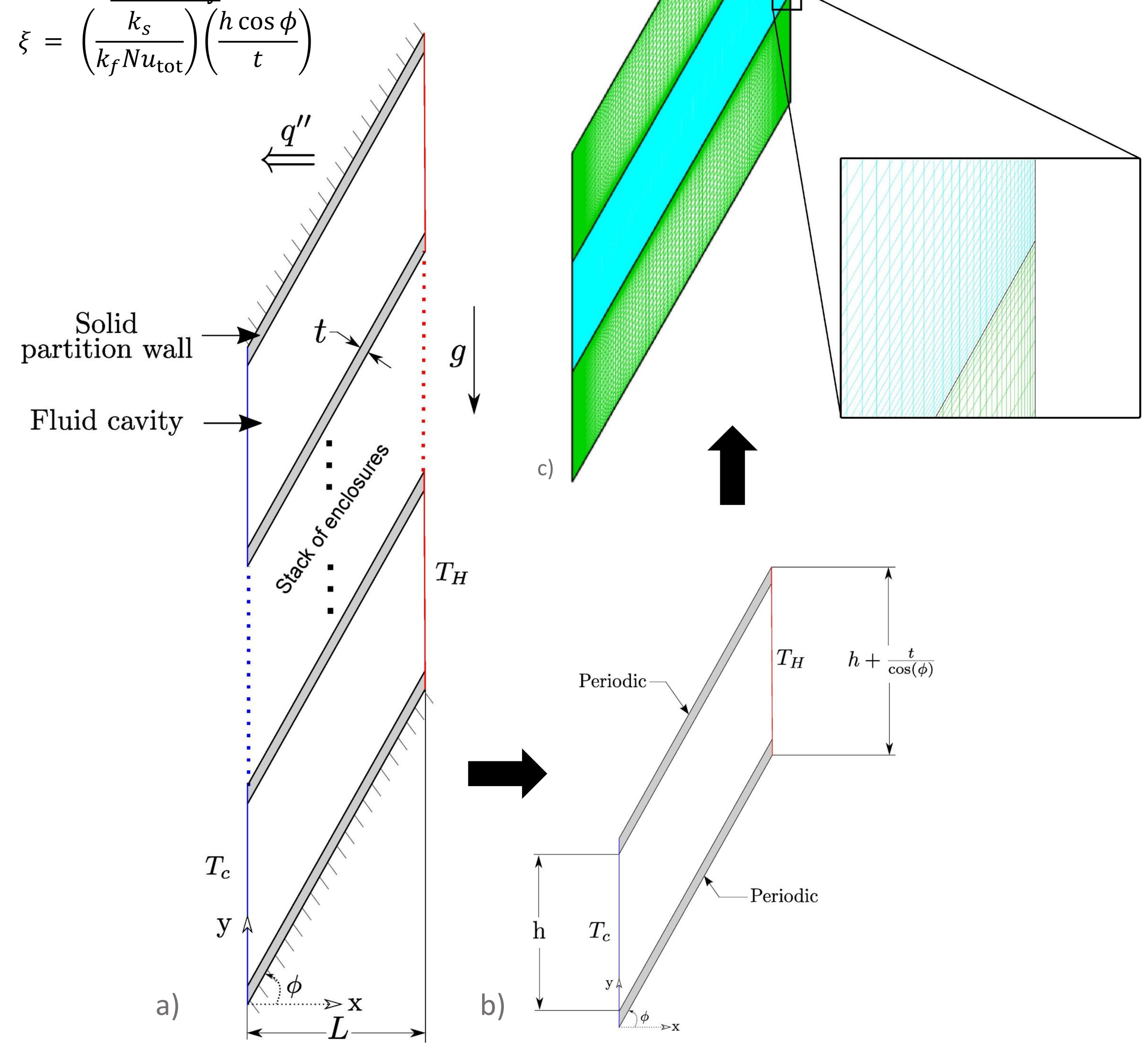
Nusselt number

$$q'_{\mathrm{ref}} = (h + t/\cos\phi)\,\frac{k_f \theta}{L}$$

$$Nu_{\mathrm{tot}} = \frac{q'_{\mathrm{tot}}}{q'_{\mathrm{ref}}}$$

Efficiency

$$\xi = \left(\frac{k_s}{k_f Nu_{\mathrm{tot}}}\right)\left(\frac{h\cos\phi}{t}\right)$$

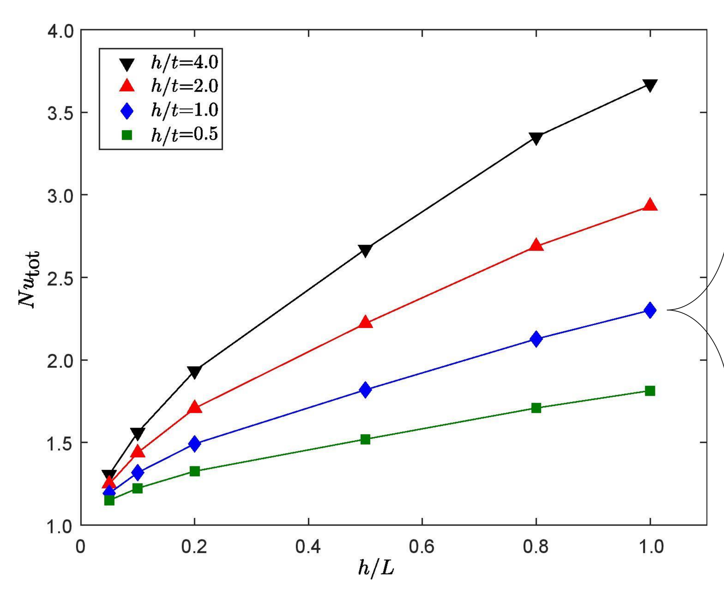


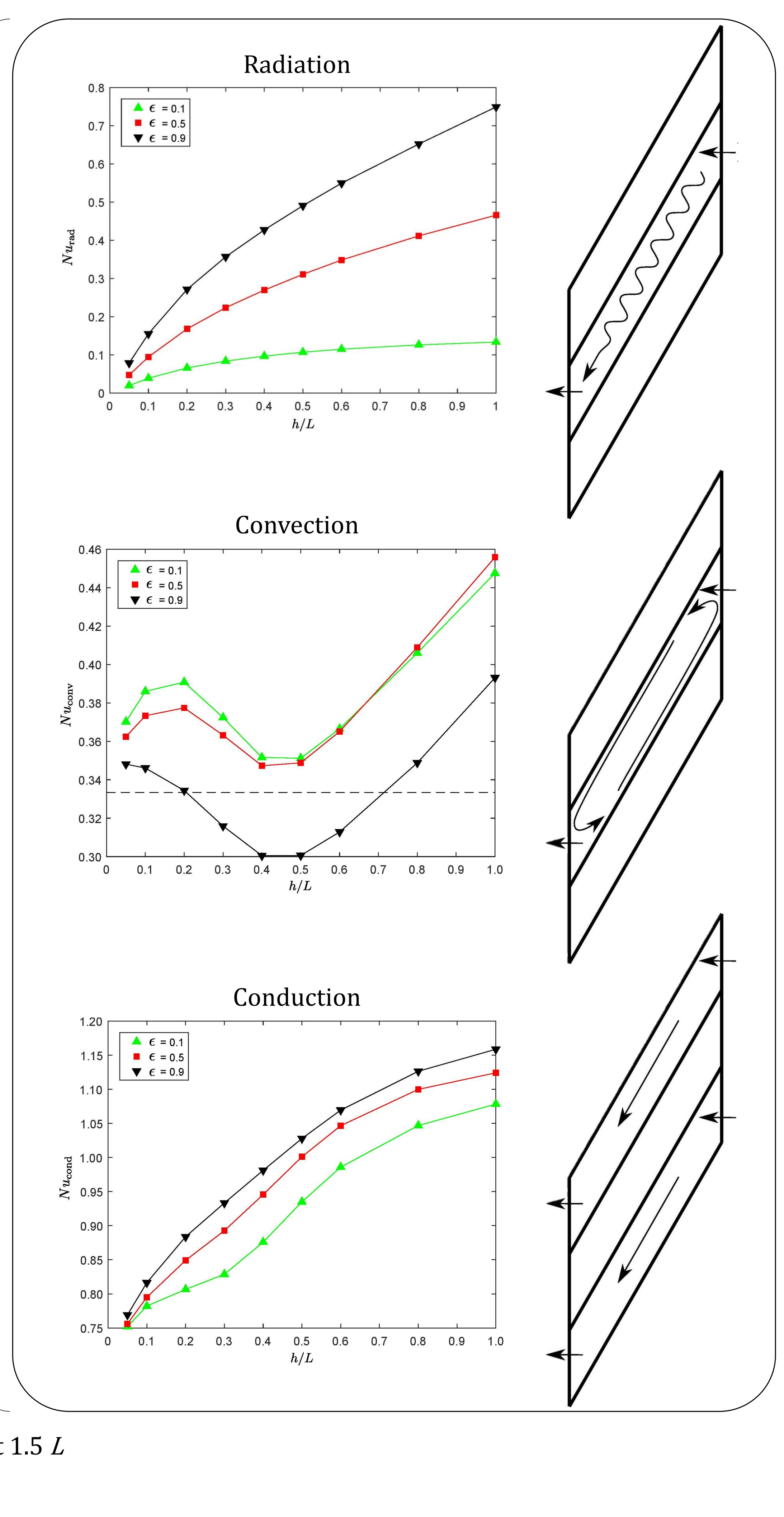
Conceptual representations of the wall configuration (a) stack of enclosure, (b) single periodic cavity, (c) mesh used for the periodic enclosure.

2. Single enclosure heat transfer analysis

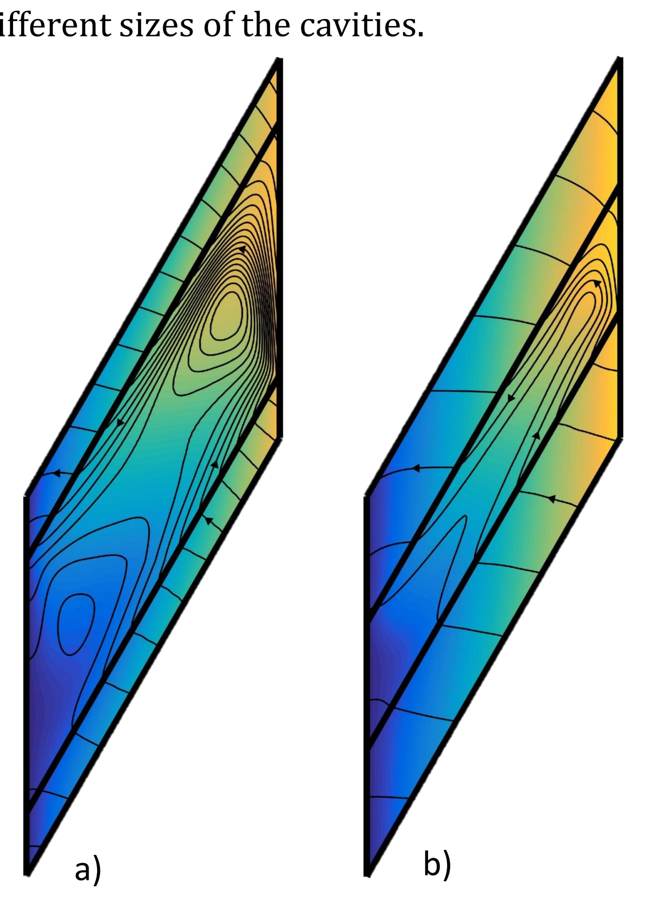
What is limiting thermal insulation ?

There are three heat transfer modes coupled together in this case: conduction, convection, and radiation. The insulation can be analyzed by changing the h/t ratio. The trend observed shows that if the ratio is increased, it leads to thinner enclosures, which then results in smaller Nusselt numbers. The conduction seems to be the most critical heat transfer mode. Indeed, about 50% of the heat transfer is present on 2/3 of the control surface (the solid portion of the partition wall). However, even if conduction is relatively important, it generally remains less important than the other two heat transfer modes in terms of heat flux (heat rate over surface).





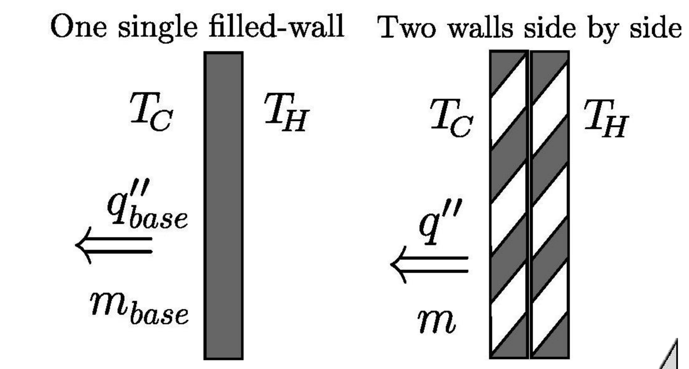
An interesting feature of the convection mode is a minimum that occurs for some geometric ratios. This trend is not induced by the effect of radiation, but rather by the presence of the periodic boundary conditions. This imposed periodicity generates a vertical heat rate. This vertical rate and the h/L ratio are illustrated by the heat lines below. Also we can see the combined conduction and convection effects for different sizes of the cavities.

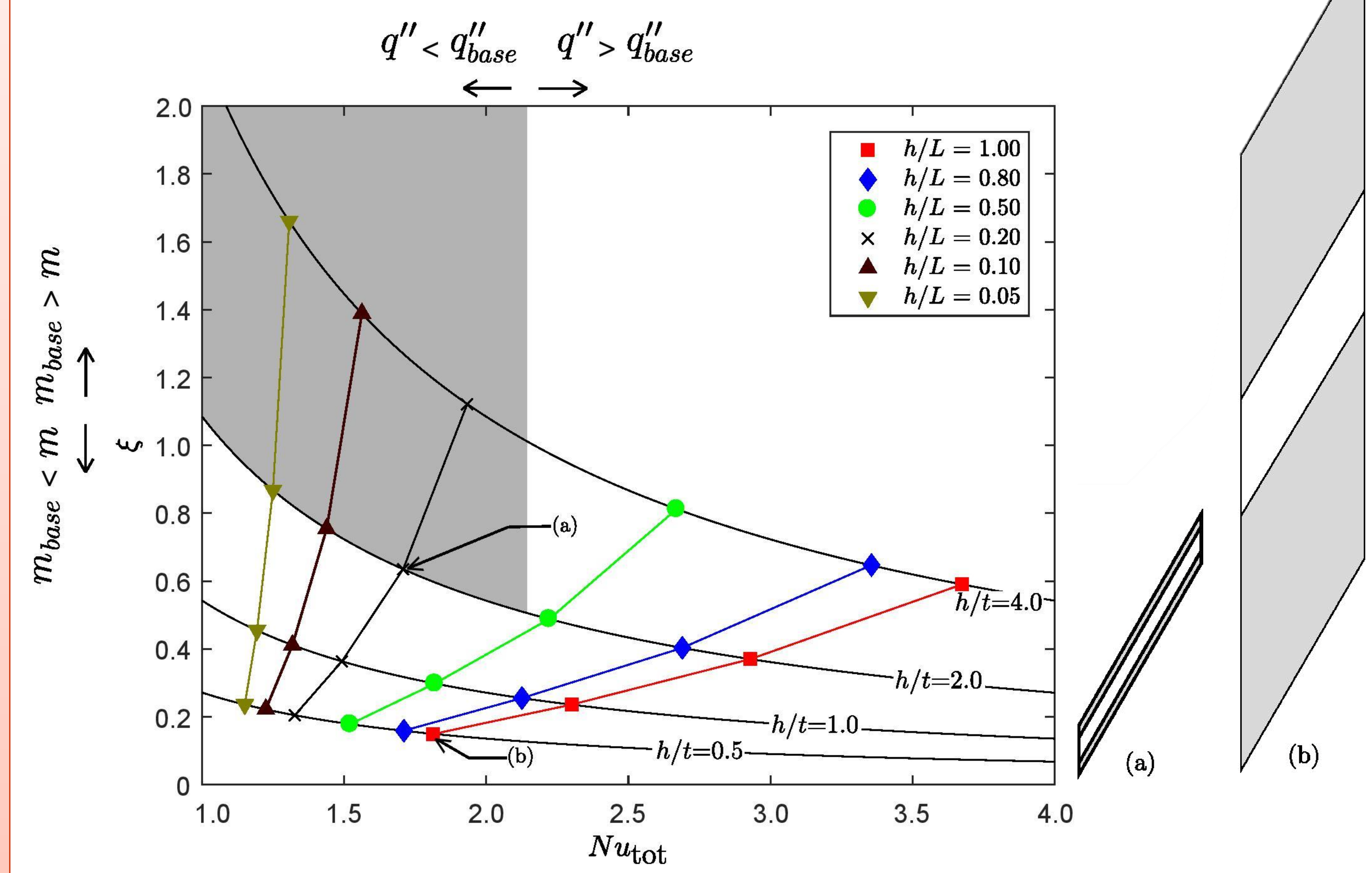


Heat lines in two enclosures that have a total height 1.5 L
(a) $h/L = 1.00$, $h/t = 4$ (b) $h/L = 0.50$, $h/t = 1.00$.

3. Two enclosure stacks side by side

If the application is not constrained by geometrical restrictions, it might be possible to get enough material savings to make another wall with it. In the figure, the grayed area represents the geometric ratios that allow enough material savings to build another wall. Thus, in this region, we get better thermal insulation by using two walls with at most the same amount of material as in a single filled wall.



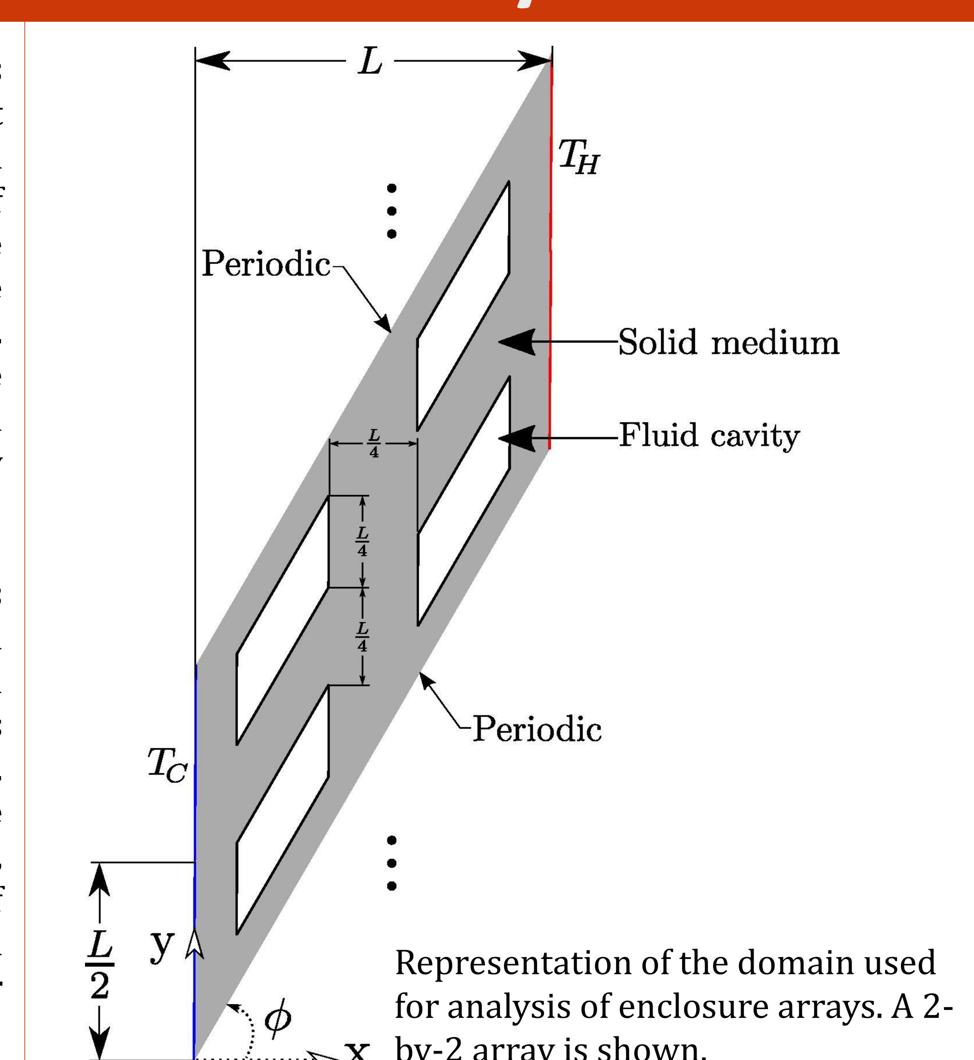


Material efficiency as a function of the Nusselt number for different h/L and h/t.

4. Enclosure arrays

The single enclosure analyses show that, to decrease the heat rate, we must use thin cavities. In this context, reducing the size of the cavities as much as possible in both directions leads to the concept of structured porosity. Therefore, with an enclosure array, a better thermal insulation along with material savings may be reachable.

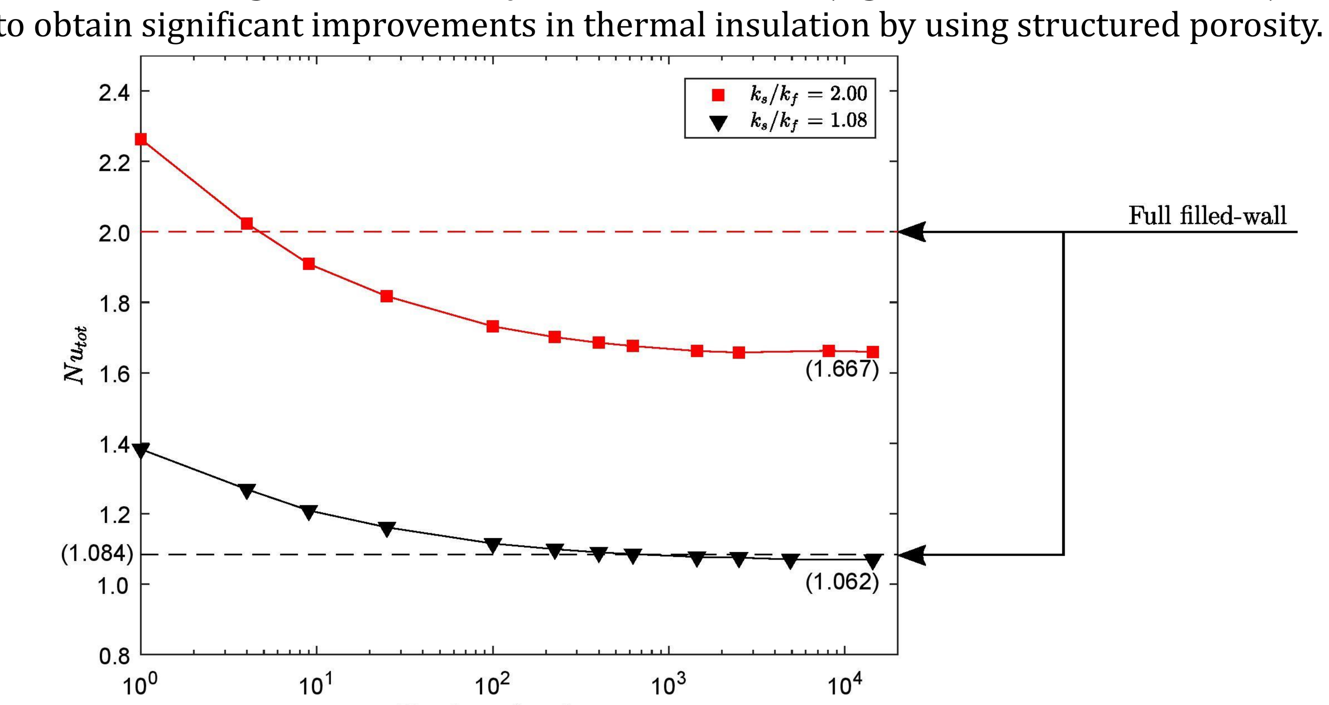
The figure on the right shows the representation of a wall section that would be composed of such an enclosure array. In this figure, a 2x2 case is considered. With this configuration, when the number of enclosure increases, the ratio between the volume of air over the volume of material remains the same, that is, 1/4 for all cases.



Representation of the domain used for analysis of enclosure arrays. A 2-by-2 array is shown.

5. Structured porosity analysis

In this specific analysis, the size of the cavities is much smaller. Therefore, the convection mode has almost no influence at all. Indeed, only radiation and conduction remain significant and limit the thermal insulation. Results show that it is merely possible to improve an already good thermal insulator (k_s/k_f near 1) although it allows some material savings. However, in context where materials with higher conductivity need to be used (e.g.: for structural stiffness), it is possible to obtain significant improvements in thermal insulation by using structured porosity.



Interestingly, because both radiation and convection becomes negligible in very small cavities, it is possible to predict accurately the heat rate with classical heat transfer theory:

$$Nu_{\mathrm{tot},\infty} = \frac{(k_s/k_f)(3 + k_s/k_f)}{2(1 + k_s/k_f)}$$