Department of Mechanical Engineering ,
Ben-Gurion University of the Negev, Israel

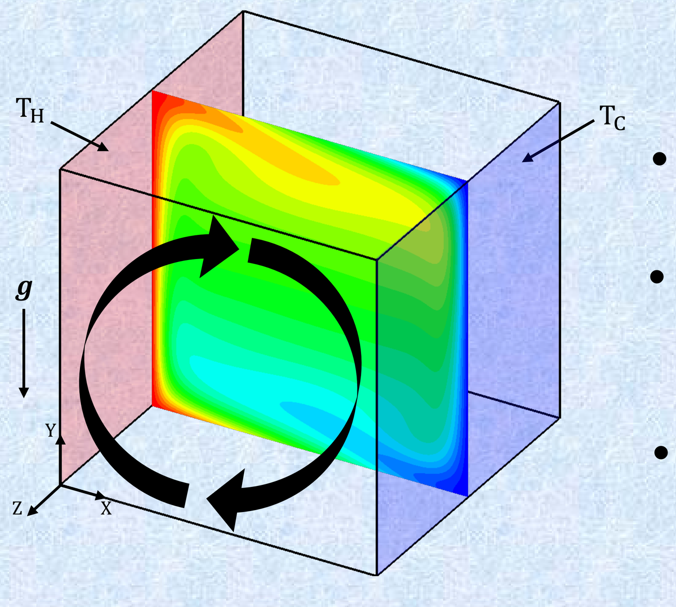
Laboratory of Computational Fluid Dynamics
and Heat Transfer

"Smart" passive thermal insulation of confined natural convection heat transfer: An application to hollow construction blocks.

Shahar Idan and Yuri Feldman

INTRODUCTION

A method for the design of "smart" passive thermo-insulating materials based on the statistical evaluation of the confined natural convection flow in the presence of heterogeneous porous media is presented. An application of the method for the enhancement of the insulating efficiency of hollow construction blocks is discussed. Confined natural convection flow developing inside a differentially heated cavity (comprising a convenient model for the air filled cavity in the mid-core of a hollow construction block) is chosen as a computational testbed. The heterogeneous porous media in the cavity are modelled by unconnected packed beds of equi- and non-equi-sized cylinders. Each cylinder is intelligently placed in the bulk of the natural convection flow to efficiently suppress the momentum in the most energetic regions of the flow. The spatial location of each cylinder is obtained by applying linear stability analysis to the 2D natural convection flow in the presence of the modelled porous media. The flow is treated by using the mesoscale approach, implicitly resolving the flow fields in the vicinity of the immersed cylinders by the immersed boundary method. The results obtained for 2D configurations are validated for realistic 3D flows. Basic statistical evaluation of the generated porous media patterns is performed in order to generalize the developed method of design of "smart" thermo-insulating materials. It is shown that the efficiency of the thermal insulation of the porous medium is closely related to the diameter of the cylinders modelling it. This study comprises an important milestone in the design and manufacture of "smart" thermo-insulating materials from available off-the-shelf porous materials.



Assumptions:

- Incompressible flow.
- Boussinesq approximation for the density variation
- Non-slip boundary conditions

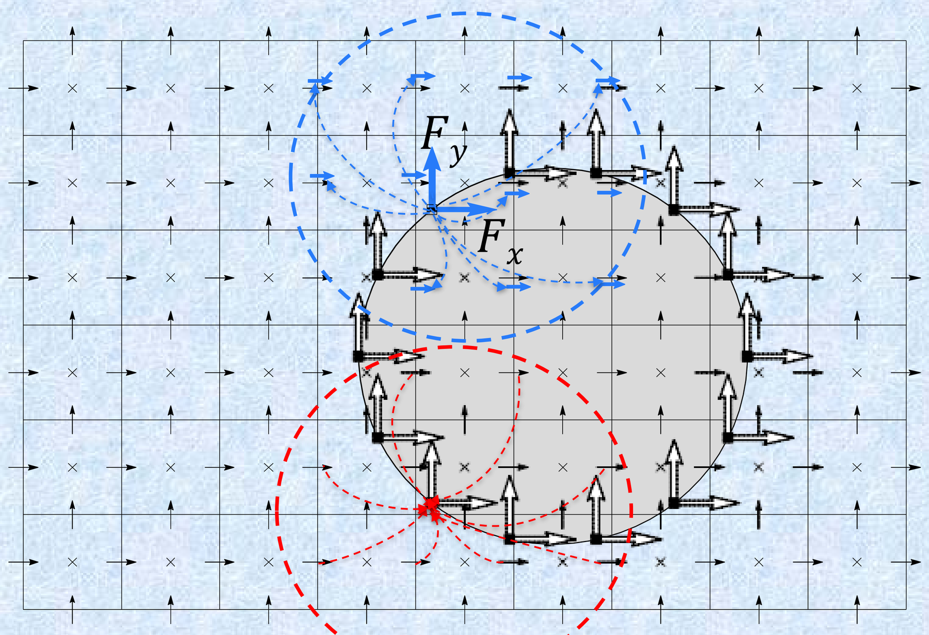
$$\nabla \cdot \boldsymbol{u} = 0$$
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla p + \sqrt{\frac{Pr}{Ra}}\nabla^2\boldsymbol{u} + \theta\vec{e}_y$$
$$\frac{\partial \theta}{\partial t} + (\boldsymbol{u}\cdot\nabla)\theta = \frac{1}{\sqrt{PrRa}}\nabla^2\theta$$

IMMERSED BOUNDARY METHOD

Steady State Augmented Equations:

$$\nabla \cdot \boldsymbol{u} = 0$$
$$(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} + \nabla p - \sqrt{\frac{Pr}{Ra}}\nabla^2\boldsymbol{u} - \theta\vec{e}_y - R_{\boldsymbol{F}} = 0$$
$$(\boldsymbol{u}\cdot\nabla)\theta - \frac{1}{\sqrt{PrRa}}\nabla^2\theta = 0$$
$$\boldsymbol{I}(\boldsymbol{u}) = \mathbf{U}_b$$

$$d(r) = \begin{cases} 0 & otherwise \\ \frac{1}{3\Delta r}\left[1 + \sqrt{-3\left(\frac{|r|}{\Delta r}\right)^2 + 1}\right] & for\ |r| \le 0.5\Delta r \\ \frac{1}{6\Delta r}\left[5 - 3\frac{|r|}{\Delta r} - \sqrt{-3\left(1 - \frac{|r|}{\Delta r}\right)^2 + 1}\right] & for\ 0.5\Delta r \le |r| \le 1.5\Delta r \end{cases}$$



$\Delta x = \Delta y \approx \Delta r$

Block-matrix form:

$$\begin{bmatrix} J_x & 0 & 0 & J_p & R_{F_x} & 0 & 0 \\ 0 & J_y & \vec{e_y} & J_p & 0 & R_{F_y} & 0 \\ 0 & 0 & J_\theta & 0 & 0 & 0 & R_Q \\ J_u & J_v & 0 & 0 & 0 & 0 & 0 \\ I_u & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & I_v & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & I_\theta & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta(u) \\ \delta(v) \\ \delta(\theta) \\ \delta(p) \\ \delta(F_x) \\ \delta(F_y) \\ \delta(Q) \end{bmatrix} = - \begin{bmatrix} F_{n_x} - \sum_j R_{jF_x} \\ F_{n_y} - \sum_j R_{jFy} \\ F_{n_\theta} - \sum_j R_{jQ} \\ F_{n_p} \\ \sum_i I_{iu_x} - U_{b_x} \\ \sum_i I_{iu_y} - V_{b_y} \\ \sum_i I_{i\theta} - \Theta_b \end{bmatrix}$$

Regularization

$$\boldsymbol{R}\left(\boldsymbol{F}_k(\mathbf{X}_k), Q_k(\mathbf{X}_k)\right) \equiv \int_S \left(\boldsymbol{F}_k(\mathbf{X}_k), Q_k(\mathbf{X}_k)\right)\cdot\delta(\mathbf{x}_i - \mathbf{X}_k)dV_{Sk}$$

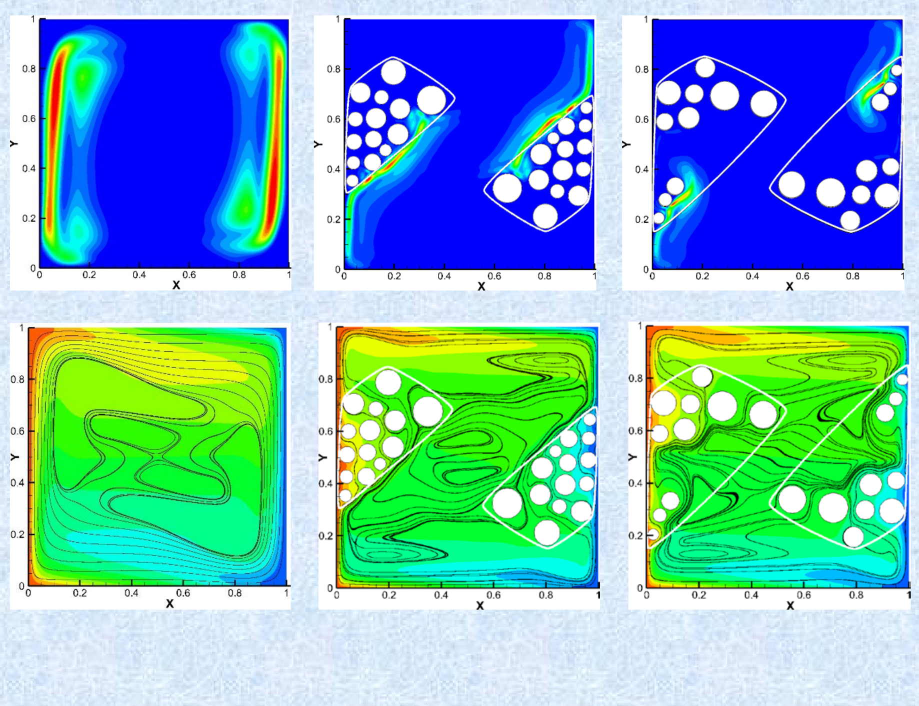
Interpolation

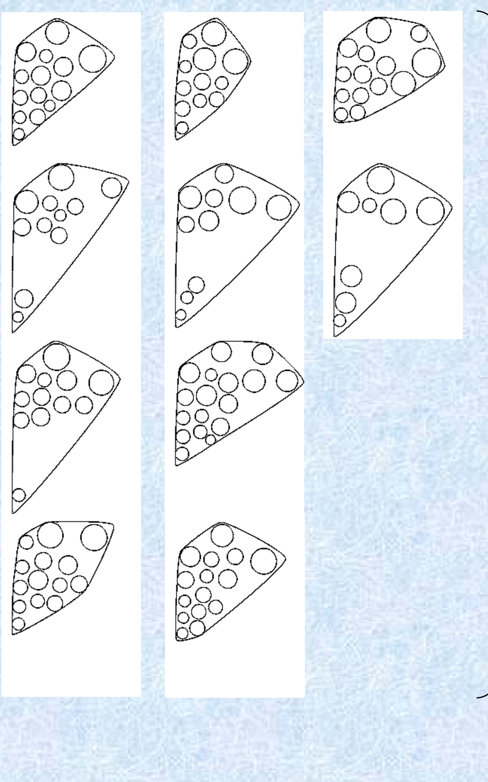
$$\boldsymbol{I}\left(\mathbf{u}(\mathbf{x}_i), \theta(\mathbf{x}_i)\right) \equiv \int_\Omega \left(\mathbf{u}(\mathbf{x}_i), \theta(\mathbf{x}_i)\right)\cdot\delta(\mathbf{x}_i - \mathbf{X}_k)dV_{\Omega i}$$

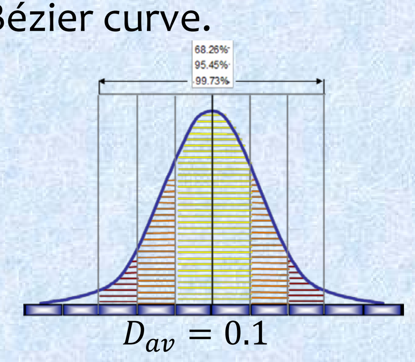
Generalizing the concept of "smart" insulators

The first step of each "smart" thermo-insulator is linear stability analysis which enables a locally suppression of the most energetic regions of convective flow based on $\boldsymbol{A}$ criterion. Each cylinder in the pattern is drawn basing on the Gaussian distribution. The overall data of the set is averaged in order to find the averaged position and porous implant. The bounding curve is obtained by utilizing De Casteljau Bézier curve.

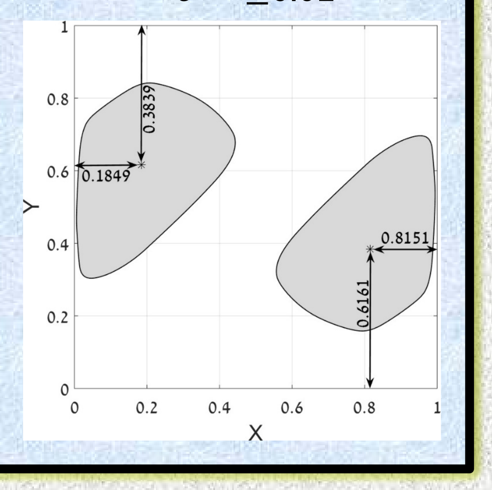
$\boldsymbol{A}$ criterion: $\boldsymbol{A} = |\widetilde{u_x}|^2 + |\widetilde{u_y}|^2$





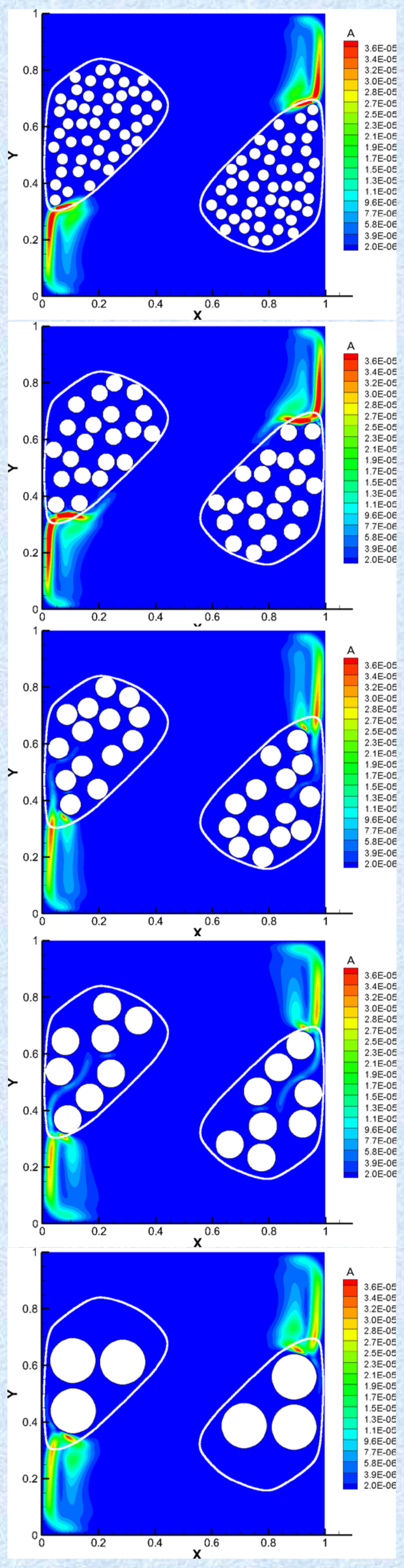


$D_{av} = 0.1$
$\sigma = \pm 0.02$

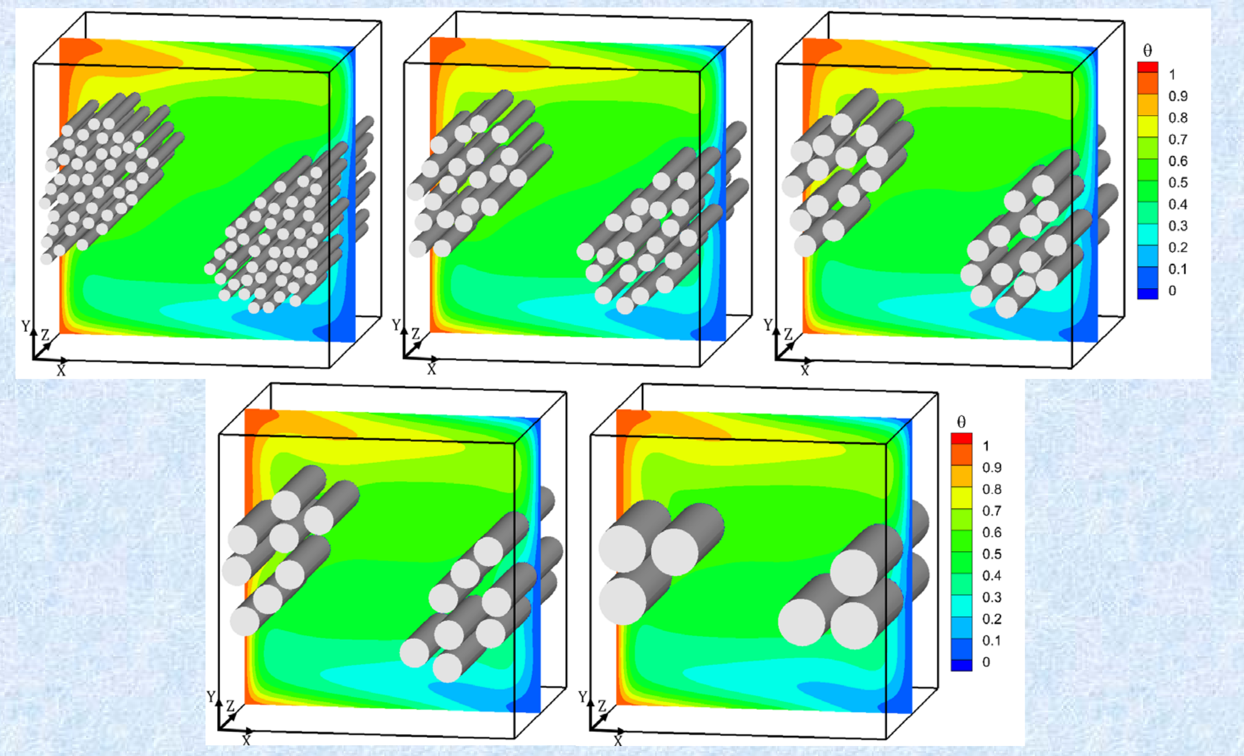


Five sets of implant created by filling in the averaged contour randomly with equally sized cylinders until the porosity of the material achieved its averaged value. Each implant in each set was tested by its ability to decrease $\overline{Nu}$.

D_{cyl}	N_{cyl}	Nu_{max}	Nu_{min}	$\overline{Nu}$	σ
0.04	94	3.8086	3.4078	3.5491	0.012
0.06	42	4.4449	3.7187	4.0300	0.105
0.074	28	6.3393	3.9832	4.6759	0.755
0.10	16	7.0326	4.1557	4.9890	0.851
0.16	6	8.0419	3.6894	5.3500	2.004

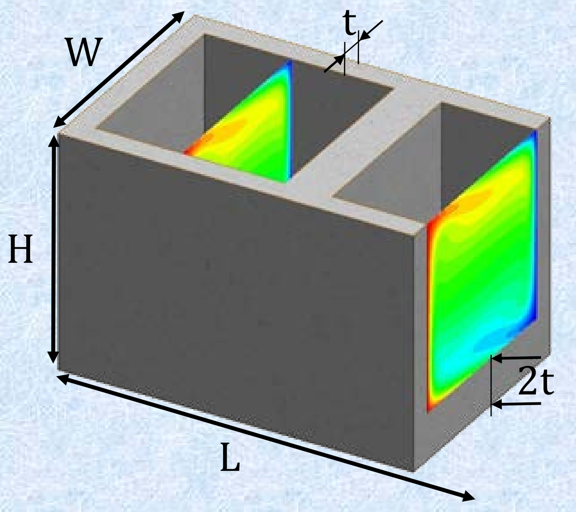


The results were validated in 3D simulation based on the direct forcing method.

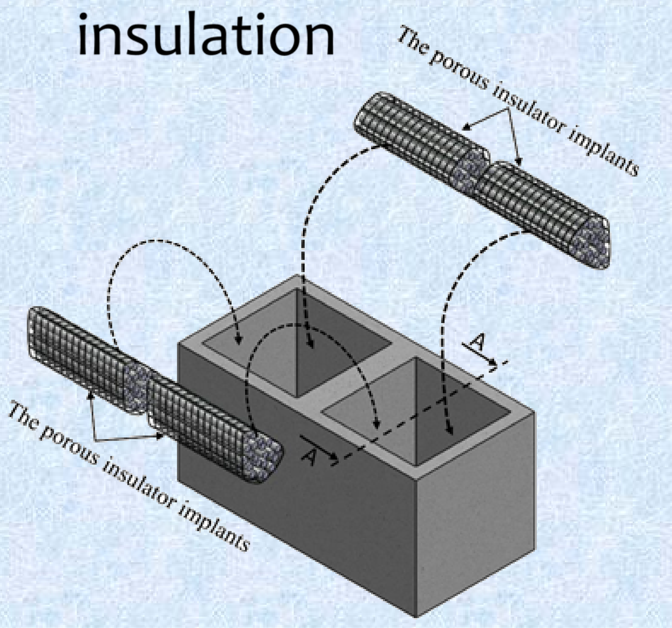


APPLICATION

Buoyancy driven flow in hollow construction block



Design based on "Smart" thermal insulation



CONCLUSION

The efficiency of the porous implant is not dominated only by its porosity rather by its ability to force the fluid to slow and disperse homogenously while passing through it, or in other words, its permeability. It is shown that porous implants modelled by the unconnected cylinders of small diameters can sustainably decrease the heat flux through the boundaries of differentially heated cavity. Those implants are also characterized by a more homogenous spatial pattern tightly related to the efficiency of thermal insulation. For this reason, among all the available porous materials only those characterized by a homogenous internal pattern should be used when producing the optimized porous medium implants. It was also verified that the insulating efficiency of construction blocks will remain the same in both hot and cold weather conditions.