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HEAT TRANSFER CHARACTERISTICS OF LAMINAR AND TURBULENT FLOWS PAST A BACK-STEP IN A CHANNEL WITH A POROUS INSERT

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Abstract. *In this work the effects of a porous insert on the heat transfer characteristics for a backward-facing step channel heated from the lower wall past the step is analyzed. The insert is placed right after the step and the influence of several parameters such as porosity, permeability, fluid-to-porous matrix conductivity ratio, insert width, etc., is analyzed. For the turbulent flow regime, a macroscopic k-ε High-Reynolds Turbulence model is used to solve the flow and heat transport equations in the porous medium. The clear and porous media are treated in a single computational domain. It is found that for some combinations of the parameters analyzed the heat transfer characteristics can be enhanced.*

Keywords. *Porous Medium, Turbulent heat transfer, Numerical methods*

1. Introduction

Many authors have investigated the use of porous inserts in recirculating flows in order to improve the heat transfer characteristics in applications such as heat exchangers, electronic device cooling, etc. In particular, Martin *et. al.* (1998) and Chan *et. al.* (2000) have extensively analyzed the case of a laminar flow through a backward-facing step channel with a porous insert. Nevertheless, for the turbulent flow regime very little is found in the literature encompassing hybrid domains, *i.e.*, clear fluid and porous medium in a unique computational domain. In this work, numerical results are presented for both laminar and turbulent flow regimes, utilizing a macroscopic flow model developed by Pedras and de Lemos (2001) and a heat transport model based on Rocamora and de Lemos (2000). For the turbulent flow regime, a macroscopic k-ε high Reynolds turbulence model is used (Rocamora and Lemos 2002). The influence of some parameters such as thickness, porosity, permeability and thermal conductivity of the porous insert on the channel's heat transfer characteristics is analyzed.

2. Flow geometry

The flow in a backward-facing step channel heated from the lower wall past the step is considered. The geometry of the problem is shown in Fig. (1) bellow. The flow enters the channel with a uniform temperature, T_{in}, and a velocity distribution, U_{in}, which corresponds to the fully developed condition for a channel $H/2$ high.

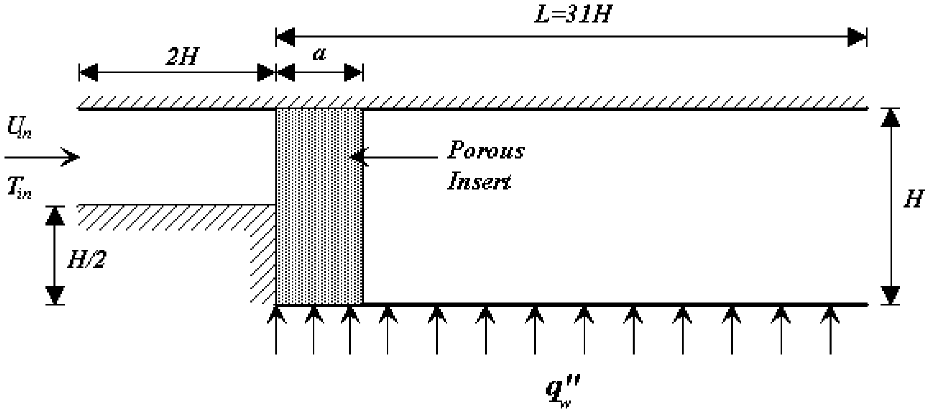


Figure 1 - Flow geometry.

The channel height is H =0.01m and the length is L =31 H . The lower wall heat flux, q''_w, is considered uniform. The thickness of the porous insert is a

2. Mathematical model

For the steady state incompressible flow through a rigid, homogeneous and saturated porous medium, Pedras and de Lemos (2001) have derived the following macroscopic turbulence flow equations:

$$\nabla \cdot (\rho \,\mathbf{\vec{u}}_D) = 0 \tag{1}$$

$$\nabla \cdot \left(\rho \frac{\mathbf{\vec{u}}_D U_{D_i}}{\phi} - \vec{t}_i \right) = s_{u_i} \tag{2}$$

$$\nabla \cdot \left(\rho \,\mathbf{\vec{u}}_D T - \frac{k_{eff}}{c_{pf}} \nabla T \right) = s_T \tag{3}$$

where ρ is the fluid density, $\mathbf{\vec{u}}_D$ is the average surface velocity ('seepage' or Darcy velocity), U_{D_i} is the velocity component in the *i* direction, k_{eff} is the effective conductivity of the saturated porous medium, c_{pf} is the fluid specific heat and T is the average surface temperature of the porous medium considering the porous matrix and the fluid in thermal equilibrium. In Eq. (2) the stress component $\vec{t}_i$ is defined as:

$$\vec{t}_i = \tau_{ij}\, \vec{i}_j \tag{4}$$

where

$$\tau_{ij} = (\mu + \mu_T) \left(\frac{\partial U_{D_i}}{\partial x_j} + \frac{\partial U_{Dj}}{\partial x_i} \right) \tag{5}$$

and the source term, s_{u_i}, which includes the Darcy-Forchheimer contribution, is given by:

$$s_{u_i} = -\left(\frac{\partial \phi P}{\partial x_i} + \frac{\phi\, \mu}{K} U_{D_i} + \frac{\phi\, \rho\, c_F |\mathbf{\vec{u}}_D|}{\sqrt{K}} U_{D_i} \right) \tag{6}$$

where K is the porous medium permeability, c_F is the form drag coefficient (Forchheimer coefficient), P is the average intrinsic pressure of the fluid and ϕ is the porosity of the porous medium. In Eq. (5) the macroscopic eddy viscosity for the porous medium is obtained using the standard *k*-ε model and is given by:

$$\mu_T = \rho\, c_\mu \frac{\left[\langle k \rangle^i\right]^2}{\langle \varepsilon \rangle^i} \tag{7}$$

where $\langle k \rangle^i$ and $\langle \varepsilon \rangle^i$ are the intrinsic volume averages of the turbulent kinetic energy and its dissipation rate, respectively. The transport equations for these two quantities as obtained by Pedras and de Lemos (2001) are written as follow:

$$\rho \nabla \cdot \left(\mathbf{\vec{u}}_D \langle k \rangle^i \right) = \nabla \cdot \left[(\mu + \frac{\mu_T}{\sigma_k}) \nabla (\phi \langle k \rangle^i) \right] - \rho\, \phi \langle \overline{\mathbf{u'u'}} \rangle^i : \nabla \mathbf{\vec{u}}_D + c_k\, \rho\, \phi \frac{\langle k \rangle^i |\mathbf{\vec{u}}_D|}{\sqrt{K}} - \rho\, \phi \langle \varepsilon \rangle^i \tag{8}$$

$$\rho \nabla \cdot \left(\mathbf{\vec{u}}_D \langle \varepsilon \rangle^i \right) = \nabla \cdot \left[(\mu + \frac{\mu_T}{\sigma_\varepsilon}) \nabla (\phi \langle \varepsilon \rangle^i) \right] - c_{1\varepsilon} \left(\rho\, \phi \langle \overline{\mathbf{u'u'}} \rangle^i : \nabla \mathbf{\vec{u}}_D \right) \frac{\langle \varepsilon \rangle^i}{\langle k \rangle^i} + c_{2\varepsilon}\, \rho\, \phi \left\{ c_k \frac{\langle \varepsilon \rangle^i |\mathbf{\vec{u}}_D|}{\sqrt{K}} - \frac{\langle \varepsilon \rangle^{i^2}}{\langle k \rangle^i} \right\} \tag{9}$$

where the surface volume average quantities are related to the intrinsic average quantities through the porosity ϕ as:

$$\langle \varphi \rangle = \phi \langle \varphi \rangle^i \tag{10}$$

and c_μ, σ_k, σ_ε, $c_{1\varepsilon}$, $c_{2\varepsilon}$ and c_k are model constants whose values are given bellow:

Table 1 - High Reynolds k-ε model constants.

σ_k	σ_ε	σ_T	c_μ	$c_{1\varepsilon}$	$c_{2\varepsilon}$	c_k
1.0	1.33	0.9	0.09	1.44	1.92	0.285

The effective thermal conductivity k_{eff} of the saturated porous medium as obtained by Rocamora and de Lemos (2000), neglecting the dispersion and tortuosity conductivity tensors, is given by:

$$k_{eff}=k_f\,\phi+k_s\,(1-\phi)+\phi\,c_{pf}\,\frac{\mu_T}{\sigma_T} \tag{11}$$

where the last term in Eq. (11) already encompasses the turbulent dispersion and turbulent thermal conductivities, k_f and k_s are the fluid and solid thermal conductivities, respectively, and σ_T is the turbulent thermal Prandtl number.

3. Numerical method

The discretization of the equations is accomplished using the finite volume method in a 2D geometry. The SIMPLE algorithm of Patankar (1980) is used to solve the flow equations. The computational domain is divided in (100x80) cells for the laminar cases and (100x40) cells for the turbulent ones. The results are considered converged when the residues are ≤ 10^{-5}.

4. Results and discussion

A summary of the cases analyzed is presented in Table (2). A combination of two porosities, two permeabilities and two porous insert thickness was considered. Only one Reynolds number was considered for the laminar regime (Re_H =800) and one for the turbulent regime (Re_H =25000). Also, only one porous matrix-to-fluid thermal conductivity ratio, k_s/k_f =3000., was considered.

Table 2 - Summary of the cases analyzed.

Case #	Re_H	k_s/k_f	ϕ	$Da=K/H^2$	a/H
l1	800.	-	-	-	-
l2		3000.	0.97	10^{-2}	0.25
l3					0.125
l4				10^{-3}	0.25
l5					0.125
l6			0.90	10^{-2}	0.25
l7					0.125
l8				10^{-3}	0.25
l9					0.125
t1	25,000.	-	-	-	-
t2		3000.	0.97	10^{-2}	0.25
t3					0.125
t4				10^{-3}	0.25
t5					0.125

In order to assess the influence of the porous inserts on the heat transfer characteristics as well as on the flow pattern for the backward facing step channel, Figures (2) and (3) show the streamlines for the laminar and turbulent cases, respectively. As can be noticed from these figures, the permeability, K , and the thickness of the porous insert, a , play a major role on the flow pattern. For the right combination of these two parameters, the recirculation bubble can be completely suppressed, as seen in cases *l4*, *l8* and *t4*. Nevertheless, the suppression of the recirculation bubble does not necessarily mean that heat transfer will be enhanced. In this work the heat transfer characteristics will be analyzed through the Nusselt number, Nu_i , calculated based on the inlet flow temperature, T_{in} , expressed as:

$$Nu_i=\frac{\left.\dfrac{\partial T}{\partial y}\right|_{y=0}\times H}{\left(T_w-T_{in}\right)} \tag{12}$$

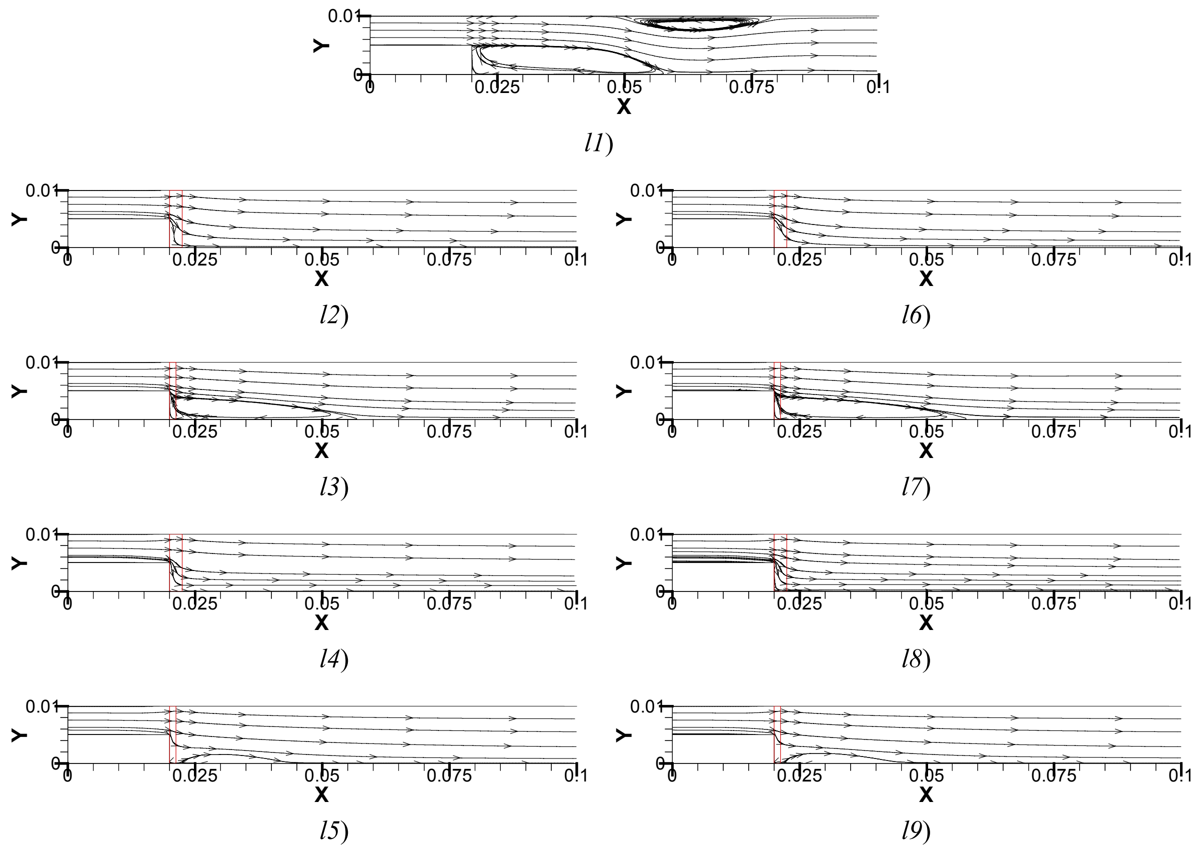


Figure 2 - Streamlines for the laminar flow cases.

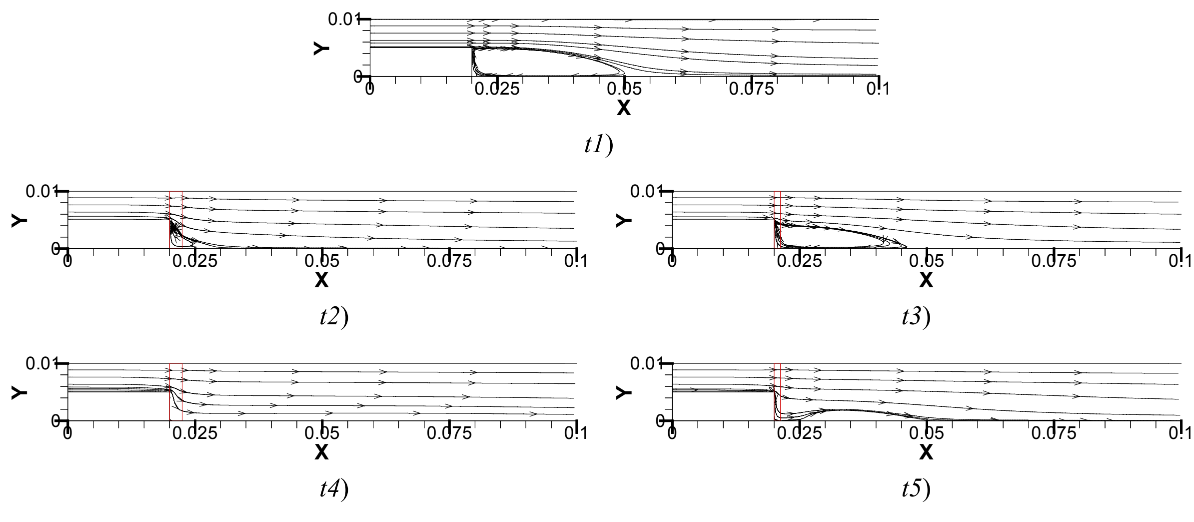
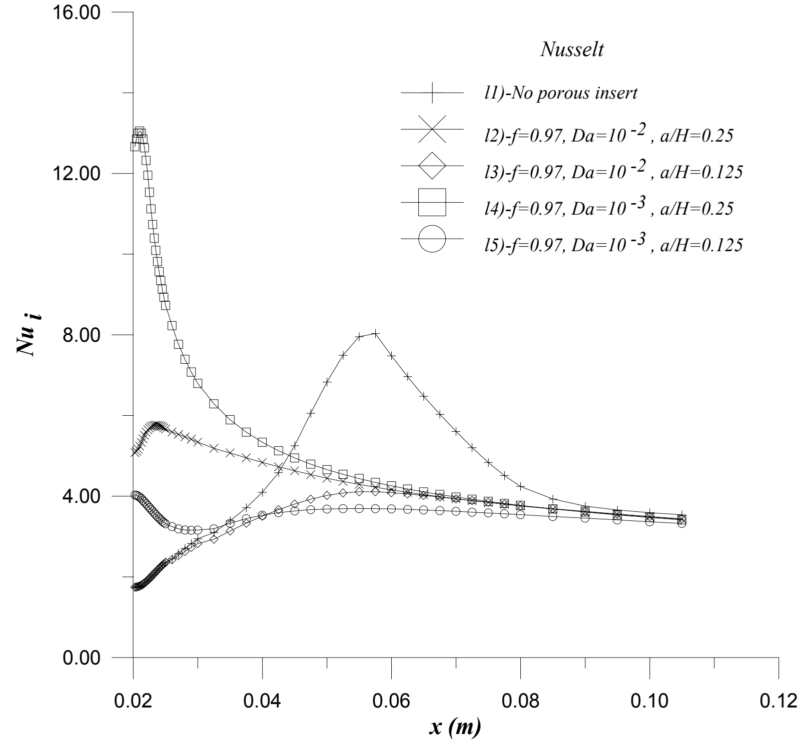


Figure 3 – Streamlines for the turbulent flow cases.

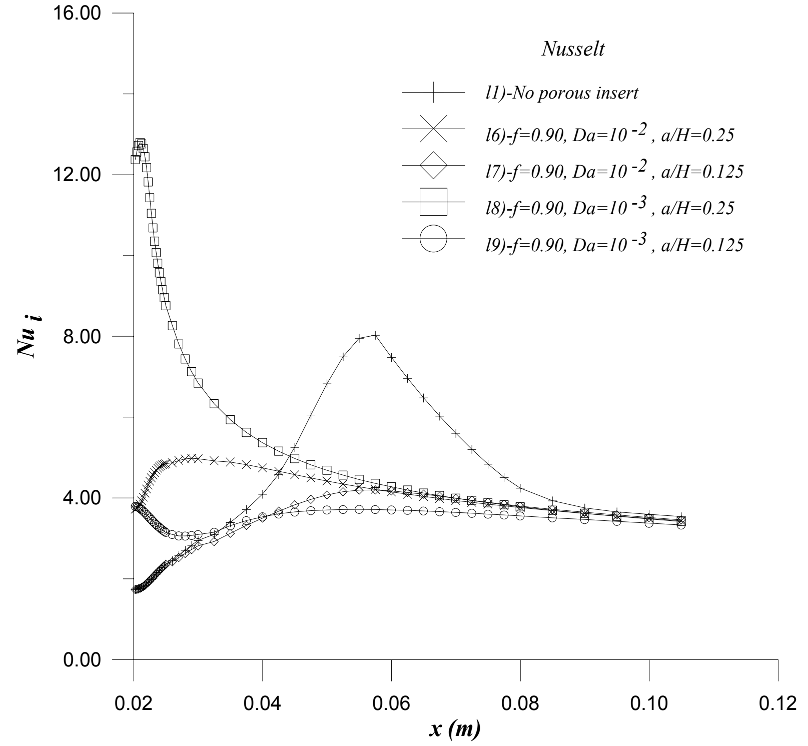
In Eq. (12) T_w is the lower wall temperature. A uniform heat flux q''_w *=2.0KW/m²* and a fluid thermal conductivity k_f *=3.08·10⁻²W/mK* were used. The temperature gradient at the lower wall is obtained considering the effective thermal conductivity, k_{eff} .

The results obtained for Nu_i are shown in Figures (4) and (5). From Fig. (4), *i.e.*, for the laminar flow, one can easily notice that for cases *l4* and *l8* there is a significant enhancement on the heat transfer right after the step due to the porous insert, compared to the case with no porous insert. This is achieved for K =10⁻⁷m² and a =0.25 H , for both porosities ϕ=0.90 and ϕ=0.97. From Fig. (2) we can observe that cases *l4* and *l8* are the ones for which the recirculating bubble is completely suppressed. Nevertheless, it should be noticed that for other combinations of parameters such as permeability and thickness of the porous insert, the heat transfer characteristics may be hindered instead of enhanced, as can be seen for cases *l3* and *l7*. This suggests that, as pointed out by Martin *et. al.* (1998), care should be exercised in designing porous inserts for inherently recirculating flows, which could result in poorer heat transfer characteristics than without the porous inserts.

For the turbulent flow regime, the curves obtained for Nu_i are presented in Fig. (5). From the cases analyzed, only the case *t4* presented an increase in Nu_i right after the step, even though it is quickly overcome by the case without porous insert. The results suggest that the insertion of a porous material in inherently recirculating flows for the turbulent flow regime, worsen the heat transfer characteristics of the channel as a whole, though it may be used to avoid a hot spot right after the step.



a)



b)

Figure 4 - Nu_i for the laminar flow cases: *a*) ϕ=0.97; *b*) ϕ=0.90.

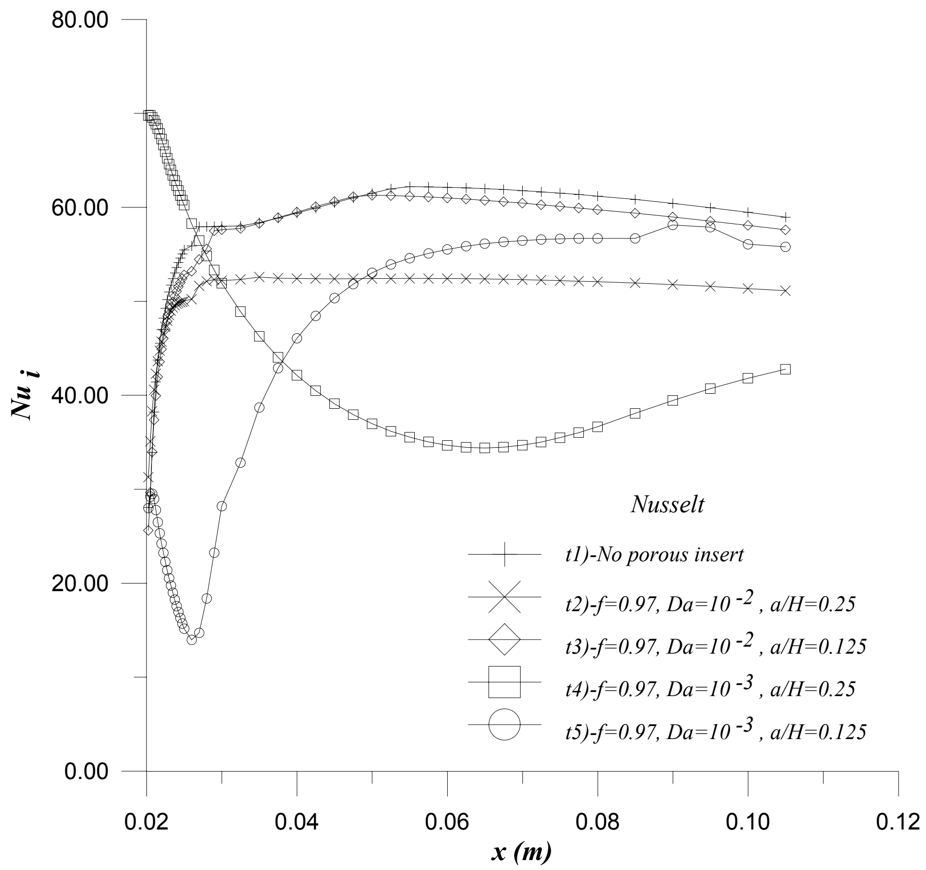


Figure 5 - Nu_i for the turbulent flow cases.

5. Conclusions

In this work numerical results for a backward-facing step channel with a porous insert were presented and an analysis of the influence of some parameters on the heat transport characteristics was performed. For the laminar flow regime the results indicated that, for some combinations of permeability and thickness of the porous insert, the heat transfer characteristics for the channel can be enhanced. They also suggest that care should be taken in designing a porous insert for inherently recirculating flows, for they can make it worse than without porous inserts. For the turbulent flow regime it seems that the placement of a porous insert tends to hinder the heat transfer characteristics, though it may be used to avoid the formation of hot spots.

6. References

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