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Technical Note

Thermal characterization of porous carbon foam—convection in parallel flow

A.G. Straatman [a,*], N.C. Gallego [b], B.E. Thompson [c], H. Hangan [d]

[a] Department of Mechanical and Materials Engineering, The University of Western Ontario, London, Ont., Canada N6A 5B9
[b] Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
[c] Foam Application Technologies Inc., Mayaguez, Puerto Rico
[d] The Boundary Layer Wind Tunnel Laboratory, The Department of Civil and Environmental Engineering, The University of Western Ontario, London, Ont., Canada N6A 5B9

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Abstract

Experiments are presented to quantify the convective heat transfer that is obtained by passing parallel airflow over a layer of porous carbon foam bonded onto a solid substrate. The increase in heat transfer is shown to be inversely proportional to Reynolds number and decreased from about 28–10% over the Reynolds number range 150,000–500,000. The heat transfer is independent of the effective conductivity over the range of conditions tested herein, and is independent of thickness for carbon-foam layers of thickness greater than 3 mm.

Keywords: Porous carbon foam; Convective heat transfer enhancement

1. Introduction

Porous carbon foam developed at Oak Ridge National Laboratory (ORNL) [1,2] is being investigated as a material to improve single and multiphase heat transfer. Carbon foam has a high effective conductivity (40–160 W/m K) [2] because of the high material conductivity of the graphitized carbon material (800–1900 W/m K). In comparison, similar porosity aluminum foams have effective conductivities of 2–26 W/m K, resulting from material conductivities of 140–237 W/m K (for various aluminum alloys) [3]. The high effective conductivity of the porous carbon foam combined with the open, interconnected pore structure is conducive to high internal heat transfer and the potential for high convective heat transfer enhancements.

Porous materials have been studied for many years for application in heat transfer (see, for example, [2–8]), however little information exists describing the heat transfer for a spherical void phase porous material. Fig. 1 gives a magnified image of porous carbon foam taken at an arbitrary cross-sectional cut [1]. The image illustrates the near-spherical void shape, the interconnected structure and the distribution of void size inside the foam. Yu et al. [9] recently proposed a sphere-centered unit-cube geometry model for porous carbon foam to describe the internal and external exposed surface area and to quantify the effective conductivity all as a function of porosity and pore diameter.

Enhancement of convective heat transfer by the use of porous materials results from the passage of fluid through the open, interconnected void structure, thereby exposing the fluid to internal surface area, which can be as large as 5000–50,000 m^2/m^3 for porous carbon foam [1]. The way to obtain maximum surface area exposure is to force all of the fluid through the foam, however this can result in

* Corresponding author.
E-mail address: astraatman@eng.uwo.ca (A.G. Straatman).

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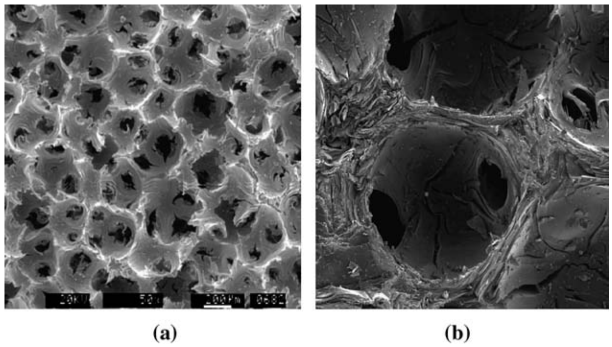


Fig. 1. (a) Scanning electron micrograph of the carbon foam surface [1] and (b) Scanning electron micrograph of the carbon foam surface of a single pore.

Table 1
Summary of properties for the carbon foam specimens tested

Specimen	Porosity (%)	Average void dia. (μm)	Highest frequency void dia.	k_{eff} (W/m K)
217 Bottom	74	310	300	108
217 Top	78	341	350	68
219 Middle-Bottom	84	643	620	64
219 Top	89	633	800	30
221 Bottom	67	473	550	245
221 Top	80	430	550	135

very high pressure drops [2]. It is also possible to obtain convective heat transfer enhancement by bonding a layer of foam to a solid substrate and allowing fluid to flow *across* the foam surface. The high effective conductivity ensures that the layer of foam readily entrains heat out of the solid substrate to be swept away by passing fluid. The passing fluid can penetrate the foam surface naturally with modest pressure drop because of the open, interconnected structure. Convective heat transfer enhancement then occurs in two ways: first due to the roughness of the exposed surface, and second due to the additional surface area exposure to fluid that infiltrates the foam. To understand the utility of this concept, it is necessary to investigate the flow and convective heat transfer under the conditions described above.

This paper presents an experimental investigation into the flow and convective heat transfer in porous carbon foam. The experiments described in this paper were designed to establish the enhancement of heat transfer that could be obtained by bonding a layer of carbon foam to a flat surface and then subjecting the surface to various heat fluxes and parallel airflows. The enhancement achieved under the conditions considered herein is based upon the *natural* infiltration of air into the carbon foam and the exposure of the infiltrated air to sub-surface area. The results of these initial tests will serve as a benchmark for future experiments done in conditions where the surface is inclined with respect to the air flow, or cases where the airflow is impinged upon the surface.

2. The carbon foam specimens

The carbon foam specimens tested in the present experiments were produced using the patented foaming process [10] and supplied by ORNL and by a POCO™. Details of the foaming and heat treatment processes, and the method used to obtain the properties is provided in [1]. Structural and thermal properties of the specimens are summarized in Table 1. The specimens are characterized by number: 217, 219 (ORNL foams) and 221 (POCO™), and by the location in the foam block (*Bottom, Middle* or *Top*) from which they were machined. Specimens denoted as *bottom* can be seen to have a slightly lower porosity (defined in % as the void fraction) than those denoted *middle* or *top* due to the gravity induced porosity gradient that is inherent to the foaming process. Since there can also be significant non-uniformity in the internal structure, the average pore diameter is not always the best indicator of the permeability of the carbon foam and thus, two different pore diameters are provided in the table: the average pore diameter and the highest frequency pore diameter.

The final column in Table 1 gives the effective conductivity of the foam specimens. Foams 217 and 219 were produced at ORNL using the same carbonization and graphitization conditions and thus have the same solid phase conductivity. Foam 221 was produced commercially at different carbonization and graphitization conditions resulting in a higher solid phase conductivity. As such, the 221 foams can not be correlated in terms of effective conductivity with the 217 and 219 specimens. The effective conductivity of the 217 and 219 specimens is seen to decrease approximately linearly with increasing porosity, as might be expected. For the 221 specimens, the effective conductivity follows the same trend, but with slightly higher effective conductivities. It is also important to note that the effective conductivity reported in Table 1 is that in the foaming direction; the conductivities in the plane normal to the foaming direction are typically about 50–75% of the values reported, and thus are still very high compared to other porous materials.

3. The experiments

Experiments have been designed to investigate two important aspects of porous carbon foam subjected to an external parallel airflow: the infiltration of air into the foam and the resulting enhancement of convective heat transfer. The infiltration of air into the foam is examined in terms of the depth of penetration and the resulting area exposure or sub-surface area recruitment. The depth of penetration of infiltrated air is established herein by conducting a series of experiments starting with a relatively thick layer of foam (10 mm) and then systematically machining away thin layers of foam material and repeating the experiments until the bare substrate is exposed. The enhancement of heat transfer is estimated by comparing the heat transfer of the exposed foam surface to that of the bare substrate once the foam has been machined away.

3.1. Theoretical basis

A heated (foam-coated or bare) plate of dimensions $l \times w$ is mounted flush into the surface of an unheated splitter plate a distance $L - l$ from its leading edge, as shown in Fig. 2. The flow is assumed to be two-dimensional on the basis that the splitter plate is much wider than the heated plate, yielding a similar profile across the entire heated section. Furthermore, the heating arrangement and control renders the plate isothermal for all conditions considered. The thermal performance of the porous carbon foam is described in terms of the Nusselt number, Nu_L, given as

$$Nu_L = \frac{hL}{k}, \tag{1}$$

where, h is the convective heat transfer coefficient, L is the boundary layer development length and k is the thermal conductivity of air evaluated at the film temperature (average of plate and ambient temperatures). The Reynolds number

$$Re_L = \frac{\rho U_a L}{\mu} \tag{2}$$

is used to characterize the airflow. Here U_a is the air speed measured upstream of the splitter plate, and ρ and μ are the density and dynamic viscosity of air, respectively, evaluated at the film temperature. Convection from a heated flat plate is a classical geometry that has been studied for more than a century leading to many correlations (see, for example, Incropera and Dewitt [11]). Heat transfer correlations for the average Nusselt number for a flat plate take the form

$$\overline{Nu_L} = C Re_L^m Pr^{1/3}, \tag{3}$$

where C is a constant, m describes the exponential dependence of Nusselt number with Reynolds number and Pr is the Prandtl number. In the laminar regime ($Re_L <$ 500,000), the exponential dependence is $m = 0.5$ and in the turbulent regime ($Re_L >$ 500,000) $m = 0.8$. In cases where the thermal and hydrodynamic boundary layers do not develop from the same location, as in the present case, a modified expression of the form

$$\overline{Nu} = \overline{Nu_L}\frac{L}{L-\xi}\left[1 - \left(\frac{\xi}{L}\right)^{(2p+1)/(2p+2)}\right]^{(2p)/(2p+1)} \tag{4}$$

can be used [12], where ξ is the unheated starting length and $p = 1$ for laminar flow and $p = 4$ for turbulent flow. For laminar flow, the modification to the Nusselt number is substantial, however if turbulent conditions prevail the modification is small since the thermal and hydrodynamic boundary layers rapidly take on the same thickness. For the present case, the roughness of the plate and foam surfaces render the flow fully turbulent even at relatively low Reynolds numbers ($Re_L >$ 200,000).

To formulate the dimensionless heat transfer in terms of the flow and heating conditions, measurements of the heat flux into the plate, Q, the plate temperature, T_p, the air temperature, T_a, and the air velocity, U_a, are required. Once obtained, the average Nusselt number is obtained as

$$\overline{Nu_L} = \frac{QL}{kA(T_p - T_a)}, \tag{5}$$

where A is the plan area of the heated plate. Since the results of importance in the present work are the enhancements obtained by bonding layers of porous carbon foam to the solid plate, all results are expressed as a ratio of the heat transfer for the foam surface with respect to the heat transfer measured for the bare (impermeable) substrate, i.e.,

$$E = \frac{\overline{Nu_{foam}}}{\overline{Nu}} = \frac{\overline{Nu_{L,foam}}}{\overline{Nu_L}}, \tag{6}$$

3.2. The test fixture

The test fixture, shown as a cross-sectional view in Fig. 3, is symmetric about its horizontal center plane and was located 0.895 m from the leading edge of a splitter plate. The fixture was designed to transfer heat from both the upper and lower surfaces into equal airstreams to minimize extraneous heat losses. The fixture was constructed from three sheets of 12 mm-thick phenolic board held together using hardwood spacers and used to support the

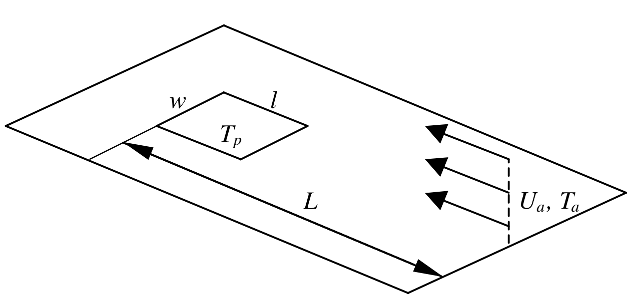
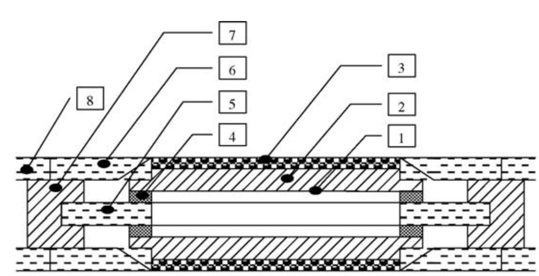


Fig. 2. Schematic of geometry under consideration giving all relevant parameters.



1 – Kapton heating element
2 – Aluminum plate
3 – Carbon foam specimen
4 – Brass spacer
5 – Phenolic support board
6 – Phenolic board
7 – Aluminum guide rail
8 – Upper surface of splitter plate

Fig. 3. Cross-sectional view of the test fixture (not to scale) to illustrate the orientation of all of the major components.

aluminum substrate on which the porous carbon foam specimens were bonded. Once in place, the upper and lower phenolic boards and the porous foam surfaces were flush with the upper and lower surfaces of the splitter plate to ensure that no boundary layer interruptions would occur. The splitter plate divided a 0.508×0.457 m wind tunnel into two equal channels so that equal airflows could be passed over the upper and lower surfaces of the test fixture.

The foam samples were bonded to the upper surfaces of aluminum plates by Materials Resources International (MRi) using their S-Bond™ process, a process designed specifically to provide highly conductive bonds between different metallic and graphitic materials. The S-Bond™ was used to minimize the contact resistance at the aluminum/carbon-foam interface. The plates and heaters were assembled using spacers of different thickness, depending upon the foam thickness, such that the upper and lower surfaces of the carbon foam were flush with the surfaces of the phenolic boards and the splitter plate. As the foam was machined away from the plate surfaces, thicker and thicker spacers were used to ensure that the carbon foam surfaces were always flush with the surfaces of the splitter plate.

3.3. Test procedure

Tests were conducted for 10, 5, 3, and 1 mm layers of carbon foam. Experiments were run for three airspeeds in the range 3–10 m/s and for two heat flux conditions in the range 20–70 W. Thus, the total number of experiments per foam specimen was 24. While the exact conditions for each specimen varied somewhat, the results for all specimens cover approximately the same range of flow and heat transfer conditions, as will be seen in the results described below.

A test was initiated by setting the airflow using the wind tunnel controls. The airspeed was monitored using a Pitot tube. The heat input was then set and temperatures of the aluminum plates and the incoming air stream were monitored until steady state was achieved. At this point, the airspeed, heat flux and temperatures of the aluminum plates and inlet and outlet flows were recorded for several minutes. The heat flux was then increased and the test repeated. Over the range of conditions considered, the maximum variation in the temperature of the aluminum plates was less than 1%, indicating that the specimens were effectively isothermal. On the basis of its high effective conductivity and the low contact resistance of the bonded interface, the carbon foam layer was assumed to be at the temperature of the aluminum substrate. Measurements of the carbon foam surface temperature were made using a portable temperature measurement device to confirm this assumption.

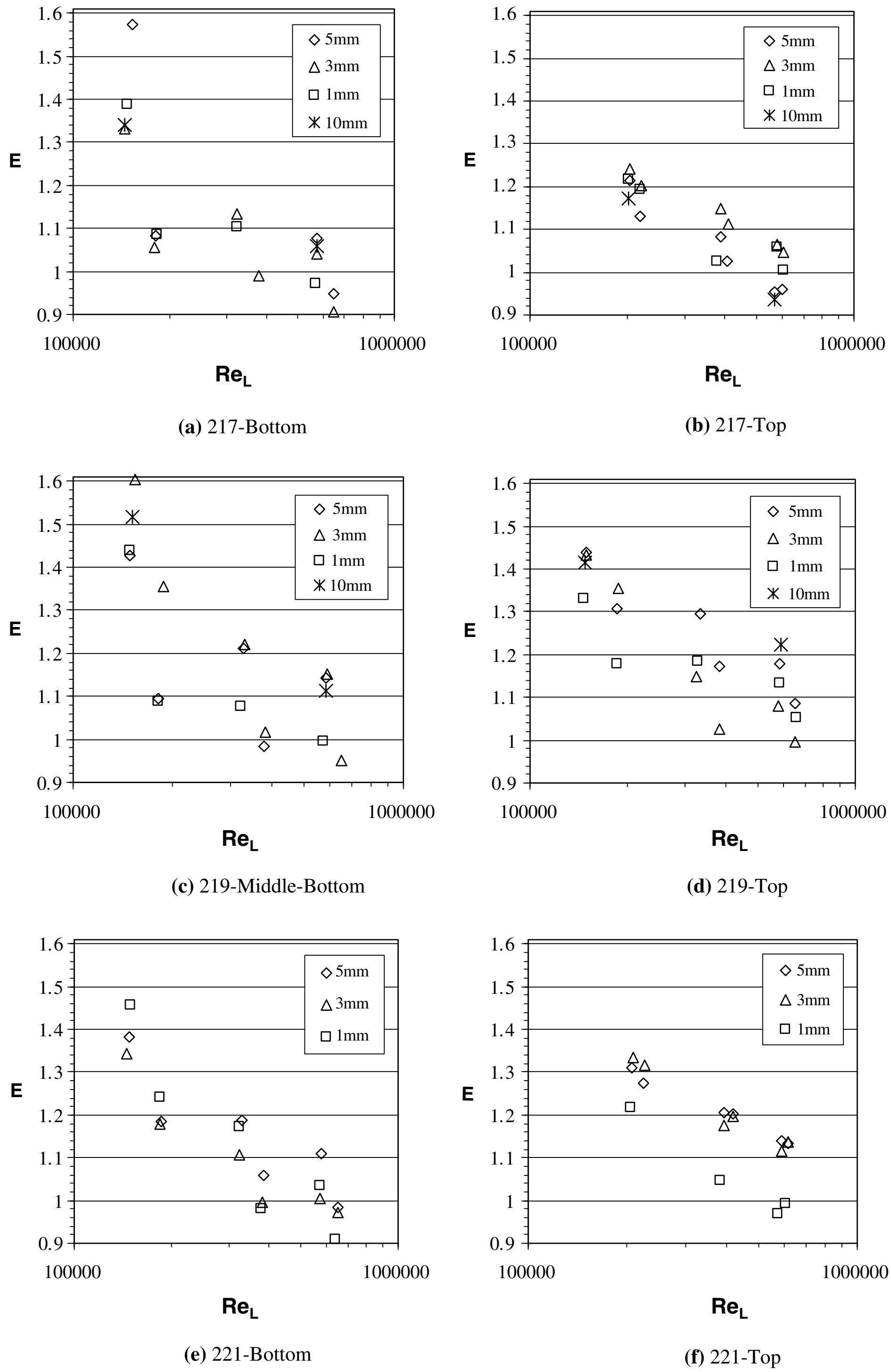
3.4. Measurement uncertainty

Velocity measurements were made at the entrance of the tunnel using a Pitot tube connected to a barocell pressure transducer and a voltmeter. Errors in velocity measurement are due mainly to the barocell zero setting and are estimated to be less then 2%. The heat input was read from the power supply and from a digital voltmeter/ammeter. The uncertainty of the heat input readings is estimated to be less than 1%. The uncertainty in the temperature measurements of the incoming air and on the upper plate for all 96 data sets was approximately 4.5%. It is important to note that the test facility was designed to minimize potential errors in the results. The test section was divided into two equal sections so that a symmetric heat transfer experiment could be conducted, thereby minimizing extraneous heat losses. To further reduce the uncertainty, all reported results are presented as a ratio with respect to the heat transfer of the bare aluminum plate, which was measured using the same procedure as the foam specimens. In this manner, any uncertainty in the input heat flux and heat losses in the test fixture are essentially cancelled out, or at least rendered small relative to other factors. It is felt that the scatter in the heat transfer enhancement data is mainly due to structural differences in the carbon foam specimens and surface irregularities due to machining.

4. Results and discussion

To verify the flow regime under which the present measurements have been conducted and to establish the present benchmark flat-plate results, experiments were carried out to obtain the heat transfer for the bare aluminum plates over the full range of heating and flow conditions considered. The results of these experiments confirmed that the average Nusselt number varies with Reynolds number according to the dependence established in previous studies for fully turbulent conditions. As stated earlier, this was anticipated due to the roughness of the profiled nose and the splitter plate surfaces over which hydrodynamic boundary layers develop.

Fig. 4 shows the convective heat transfer enhancement for the carbon foam samples described in Table 1. The plots in Fig. 4 contain complete data for 5, 3 and 1 mm of foam and for clarity, only selected data for 10 mm, since the results are similar to that for thinner foam layers. All of the plots indicate some enhancement of convective heat transfer, although there is significant scatter on any given plot. Despite the scatter, there appear to be trends in all cases with respect to foam thickness and Re_L. The results for different foam thickness are very important. At the outset, the purpose of testing different foam thicknesses was to attempt to establish the depth of penetration of air into the foam. The present experiments show that the heat transfer is not a strong function of the foam thickness; heat transfer enhancements that were obtained with 10 mm of foam were also obtained, on average, for 5 and 3 mm of foam, as shown in Fig. 4a–d. At 1 mm foam thickness, the results are seen, on average, to degrade somewhat (and be more highly scattered), probably due to the presence of bonding material in the pores. The observations of heat transfer



(a) 217-Bottom (b) 217-Top

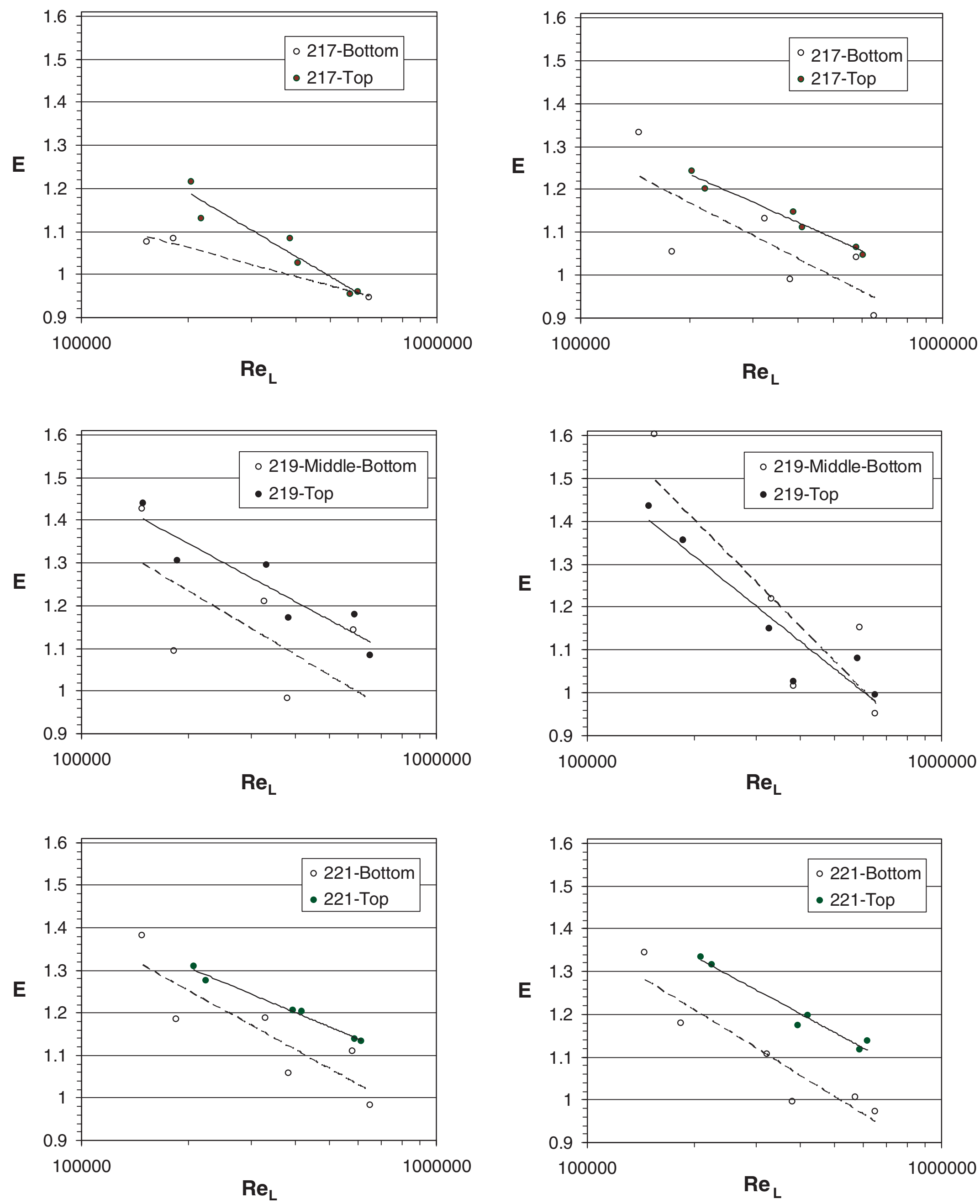
(c) 219-Middle-Bottom (d) 219-Top

(e) 221-Bottom (f) 221-Top

Fig. 4. Results of heat transfer enhancement as a function of Re_L for all of the foam specimens described in Table 1.

with respect to foam thickness suggest two things: that the foam temperature is the same as the temperature of the aluminum substrate independent of foam thickness due to its low conductive resistance, and that the depth of penetration of air into the foam is relatively small for parallel flow conditions. When comparing the plots in Fig. 4, it is evident that, on average, there is no decisive advantage for using more than 3 mm of foam. This means that the depth of penetration of air into the foam is as little as 3–5 pore-diameters (assuming that the first 1 mm of foam is filled with bonding material). Though the penetration depth of air is certainly dependent upon the pore diameter and porosity of the foam, it is difficult to resolve this influence due the non-uniformity of pore diameter and the difficulty of machining the foam thickness to within small fractions of a millimeter. Thus 3 mm serves as a first approximation for the desired thickness of porous carbon foam for parallel flow conditions. It is important to note that the depth of penetration of air into the foam is expected to be a strong function of the incidence of the foam surface with respect to the air flow, i.e. in the limit of an impinging airflow, the air would penetrate the foam surface much more deeply leading to much higher enhancements in convective heat transfer.

Concerning the dependence on Re_L, the enhancements shown in Fig. 4 are seen to be higher for low air speeds (about 1.28 on average) and lower for high air speeds (about 1.10 on average), with an approximately monotonic variation. This trend can be explained in terms of the near-surface activity and the relative air flows in and across the porous carbon foam. In a parallel flow, the air is not *driven* into the foam, but rather the roughness of the foam surface produces disturbances of the sub-layer resulting in the production of near-surface eddies. The eddies actively penetrate the foam setting up (weak) pressure gradients near the foam surface,



5mm foam layer

3mm foam layer

Fig. 5. Comparison of convective heat transfer enhancement for the Bottom and Top specimens of Foams 217, 219 and 221, respectively. The plots on the left correspond to 5 mm layers and the plots on the right correspond to 3 mm-thick layers of carbon foam. The dashed line gives the approximate trend for "Bottom", while the solid line is for "Top" in each case.

thereby causing air to pass through the interconnected pore structure before returning to the free stream. The air that passes through the foam is exposed to the large internal surface area thereby enhancing the net convective heat transfer of the specimen. At low air speeds (i.e. low Re_L), the momentum of the near-surface eddies is low, but the relative amount of air passing through the foam is "significant" with respect to the air flow across the exposed surface of the foam. At high air speeds, the near-surface eddies are very energetic, but the amount of air passing through the foam is "small" with respect to the external flow. As such, the enhancement of convective heat transfer is higher at low air speeds and lower at high air speeds. It is likely that at very high air speeds, the enhancement in heat transfer performance would be due only to the increased roughness and exposed surface area.

Fig. 5 compares the *Bottom* and *Top* specimens of each of the numbered blocks for foam layers of thickness 5 mm and 3 mm. From these plots, even more insight is gained concerning differences in heat transfer enhancement due to changes in the effective conductivity and the openness of the foam. As discussed above, the influence of the effective conductivity appears to be minimal for the specimens considered. However, it is expected that specimens with a very low effective conductivity would degrade the heat transfer from the substrate since there would be minimal means for conducting heat into the foam to be convected away; in this case the foam would serve more to insulate the substrate from the passing airflow. For the specimens considered in the present experiments, the high effective conductivity renders the foam virtually isothermal at the substrate temperature. Though this is expected to be a function of the flow incidence and flow condition, the observation concerning the insensitivity of the heat transfer enhancement to effective conductivity is significant since the time and cost of graphitizing the porous carbon foam is a function of the desired solid phase conductivity.

In terms of the openness of the foam, Fig. 5 shows that in general, the higher porosity, larger pore diameter foam layers produce the greatest enhancements in heat transfer. This was an anticipated result since a more open foam structure has a rougher exposed surface (higher friction coefficient) and fosters the infiltration of air and the subsequent exposure to internal surface area. The roughness of the exposed surface influences the activity of the near-wall flow: the more rough and irregular the exposed surface, the more energetic the fluid motions and the higher the infiltration into the foam. Obviously, continuous increases in the openness of the foam will not lead to continuous enhancements in the convective heat transfer, since increased openness results in a reduction of solid material for conduction and a reduction of internal surface area for convective exchange. The optimal openness for foam is that which yields a balance between the conductive and convective resistances.

5. Closing remarks

An experimental study was conducted to quantify the convective heat transfer enhancements that can be obtained by bonding a layer of porous carbon foam to a solid metal substrate. The following main points are made to summarize the present experimental results:

1. The heat transfer enhancement was not a strong function of the foam thickness; enhancements observed for 10 mm of foam were also observed (on average) for 5 and 3 mm of foam. Due to the high effective conductivities of the foam specimens considered, the conductive resistance of the foam was insignificant and the foam layers were essentially isothermal at the temperature of the aluminum substrate. Thus, the depth of foam required to obtain the best heat transfer enhancement is selected based upon the depth of penetration of air, which *for parallel flow applications* was deduced to be approximately 3 mm.
2. At the lowest Re_L considered, the average enhancement of convective heat transfer was approximately 28%; at the highest Re_L considered, the average enhancement of convective heat transfer was approximately 10%. The trend from low to high Re_L was approximately monotonic. While the activity generated near the rough foam surface is a function of Re_L, the heat transfer was observed to be a stronger function of the relative airflow inside the foam and passing across the foam.
3. The comparisons indicate that on average the higher porosity specimens perform better than the lower porosity specimens due to the higher surface roughness and the more open structure of the foam. The higher surface roughness fostered the production of energetic near wall activity, which penetrated the foam surface thereby taking advantage of the subsurface area for convective heat transfer.

The results of the present study serve as a benchmark for all subsequent experiments at different airflow incidence angles and for different flow conditions.

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