Thermal/Fluid Characteristics of Elliptic Cross Section Filament Box Lattice Matrices as Heat Exchanger Surfaces

Deepti R. Sarde* and Christopher M. Herald†

University of Nevada, Reno, Reno, NV-89557

Richard A. Wirtz‡

University of Nevada, Reno, Reno, NV-89557

The thermal and fluid characteristics of elliptic cross section filament box lattices are studied. Analytical models for porosity and specific surface area are developed and are expressed in terms of six dimensionless parameters. Numerical simulations are performed to evaluate the flow and thermal characteristics of these structures deployed as heat exchanger matrices. The flows considered are laminar with Reynolds number ranging from 30 to 150. Friction factors and Stanton numbers are calculated from the simulated flow fields. The effect of streamlining the filaments via ellipticity is discussed by comparison with circular cross section filament box-lattices and three-dimensional filament woven structures.

Nomenclature

\begin{align*}
\text{c} &= \text{Specific heat coefficient of the fluid} \\
\text{D} &= \text{Diameter} \\
\text{f} &= \text{Friction factor} \\
\text{h} &= \text{Heat transfer coefficient} \\
\text{p} &= \text{Pressure} \\
\text{P} &= \text{Filament pitch} \\
\text{Pr} &= \text{Prandtl number} \\
\text{q} &= \text{Heat transfer rate} \\
\text{r} &= \text{Filament minor radius} \\
\text{R} &= \text{Filament major radius} \\
\text{S} &= \text{Surface area} \\
\text{St} &= \text{Stanton number} \\
\text{T} &= \text{Temperature} \\
\text{u} &= \text{Flow velocity} \\
\text{V} &= \text{Velocity or Volume} \\
\text{x, y, z} &= \text{Coordinates} \\
\text{\beta} &= \text{Heat transfer surface area-to-volume ratio} \\
\text{\varepsilon} &= \text{Porosity} \\
\text{\theta} &= \text{Angle} \\
\text{\mu} &= \text{Molecular viscosity} \\
\text{\nu} &= \text{Kinematic viscosity} \\
\text{\rho} &= \text{Fluid density} \\
\end{align*}

Subscripts

* Graduate Student, Mechanical Engineering Department, email: sarded@unr.nevada.edu, AIAA Member
† Associate Professor, Department of Mathematics and Statistics, email: herald@unr.edu.
‡ Professor, Mechanical Engineering Department, email: rawirtz@unr.edu, AIAA Member.
I. Introduction

Compact heat exchanger performance is largely controlled by surface area-to-volume ratio, $\beta$ [1]. Structured porous media such as box lattices [2], plain-weave screen laminations [3] or three-dimensional woven mesh structures [7] can be configured to have a wide ranging porosity ($\varepsilon$), a large specific surface area and effective thermal conductivity in a particular direction, together with specified structural characteristics. Such structures, when implemented in heat exchanger applications, produce high $\text{ntu}$-values because of the large specific surface area inherent to the media.

Tong and London [4] reported measurements of friction factor and mesh heat transfer coefficient for air flowing through inline plain-weave screen laminates and staggered cross-rod matrices (no interweaving). These results are reported in Kays and London [1]. Xu and Wirtz [5, 6] have developed analytical models of $\varepsilon$, $\beta$ and the in-plane component of effective thermal conductivity for screen laminates consisting of bonded plain-weave and diamond-weave screens. Their work shows that plain weave screen laminates can be configured to have a relatively large specific surface area. Effective thermal conductivities of anisotropic screen laminates such as diamond weaves are found to approach 78% of base material values. Wirtz and coworkers [7] employed a three-filament stacked weave configuration exchanger surface. These are very dense structures, with metal fractions, $(1 - \varepsilon)$ that can range from 0.69 to 0.786 and $2.36 \leq \beta_d \leq \pi$. Prototype aluminum filament stacked weaves with one filament ($D_v=0.76\text{mm}$) having twice the diameter of the other two have $\beta = 4680 \text{m}^{-1}$ and $ke = 84 \text{W/mK}$. Park et al [3] (screen laminates) and Wirtz et al [7] (3-filament weaves) found that these structures have Stanton number characteristics that are comparable to other compact heat exchanger surfaces, and it can be shown, based on Park et al’s. work [3] that the performance of such structures, deployed as heat exchanger surfaces is approximately proportional to $ke \beta$, so exchanger surfaces having both large specific surface area and effective thermal conductivity are expected to exhibit superior thermal performance.

Box lattice structures are open-cell matrices consisting of mutually perpendicular, group-interconnected filaments. Balantrapu et al. [2] considered sub-millimeter scale box lattices having circular cross section, thermally conductive filaments. They have shown that metal fraction, dimensionless specific surface area and dimensionless effective thermal conductivity can range as: $0 \leq 1 - \varepsilon \leq 0.94$, $0.93 \leq \beta D \leq \pi$ and $0 \leq Ke \leq \pi/4$. Gullbrand et al. [8] considered laminar and turbulent convection in circular cross section filament box lattices. Their work shows that steady laminar flow persists up to at least a Reynolds number of 100, with transition to unsteady flow at a Reynolds number of 300. In the current work box-lattices with elliptic cross section filaments are considered. Geometric models for porosity and specific surface area are developed. Numerical simulations are performed to evaluate flow and thermal characteristics. To study the effect of adding ellipticity to the filaments, friction factors and Stanton numbers are compared to the circular cross section filament case [8]. Since transition from laminar to turbulent flow is expected to occur in the range of mesh Reynolds number. 150 $\leq$ Re $\leq$ 300 [9], the flows considered for the present study are contained in the laminar regime with $30 \leq$ Re $\leq$ 150. The mesh Reynolds number is calculated as $Re = \frac{\rho V D h \lambda}{\mu}$, where $\rho$ is the fluid density, $V$ is the pore-average velocity, $D_h=4\varepsilon/\beta$ is the mesh hydraulic diameter and $\mu$ is the molecular viscosity.

In the present study numerical simulations are performed on interconnected elliptic cross section filament weaves with dimensions: $a_x=1$, $a_y = a_z = 3$, $P/R = 3.1$ and $\varepsilon = 0.4$ and $\beta e = 1.161$ where $r_e$ is the effective radius and $a$, $P$ and $R$ are the elliptic cross section filament aspect ratio, pitch and major radius, respectively.
II. Geometric Description

Figure 1 shows a box lattice of thickness $t$ and width $H$. Mutually perpendicular elliptic cross section filaments are aligned with $x$-, $y$-, and $z$-axes. The filament pitch is $P$ and the filaments have major and minor diameters: $2R$ and $2r$ respectively, aligned to facilitate flow through the array. Conduction is presumed to be primarily in the $y$-direction while coolant flow is presumed to be in the $x$-direction. Consequently heat flow is by conduction along the axis of the $y$-filaments and then by convection to the coolant, where the $x$- and $z$-axis filaments act as fins.

As an example application of this technology, imagine that the box lattice matrix shown in the Figure is deployed as an area enhancement between the plates of a plate-fin heat exchanger (plate spacing $= H$). Then, heat flow would be by conduction from the plates into the lattice structure, with subsequent convection to the coolant.

III. Analytical models

Analytical models for porosity and specific surface area are developed by considering the unit cell shown in Fig. 2. Considering a unit cell reduces the complexity of the problem. The dimensions of the unit cell are $P_x P_y P_z$. The unit cell element consists of a $y$-direction elliptic cross section cylinder having major and minor diameters $2R_y$, $2r_y$ respectively and length $P_y$ together with a cruciform shape, which includes the $x$-direction and $z$-direction elliptic cylinders. The $x$- and $z$-direction filaments have $2R_x$, $2r_x$, $P_x$, and $2R_z$, $2r_z$, $P_z$ dimensions respectively. For the present study it is assumed that $2R_y = 2R_z$ and $2r_y = 2r_z$. It is noted with reference to Fig. 2 that physically realizable structures such as the one shown in Fig. 1 must have $2R_x \leq P_y$, $2r_x \leq P_z$, etc.

A. Porosity

A Geometric model for porosity for anisotropic box lattices is developed in terms of metal fraction of a single unit cell,

$$1 - \varepsilon = V_{\text{Solid}} = \frac{V_{\text{Solid}}}{P_x P_y P_z}$$

To calculate the volume of solid in the unit cell, individual cylinders in the $x$-, $y$- $z$- direction are considered. Surplus material from $x$- and $z$-direction filaments is removed as shown in Fig. 3. The remaining components are assembled to form the solid shown in Fig. 2. The solid volume can then be written as
Fig. 3 Required volumes of cylinders in (a) x-direction (b) y-direction and (c) z- direction filaments to construct the cruciform

\[ 1 - \varepsilon = V_{yc} + V_{Tx} + V_{Tz} \]  

where

\[ V_{yc} = \frac{\pi R_y r_y P_y}{P_x P_y P_Z} \]  

\[ V_{Tx} = V_{xc} - V_{xp} \]  

\[ V_{Tz} = V_{zc} - (V_{zp} + V_{zfp}) \]

\( V_{Tx} \), \( V_{yc} \) and \( V_{Tz} \) are the final volumes of the filaments in y-, x- and z- directions, respectively, normalized by the volume of unit cell. In Eq. (4) \( V_{xc} \) is the volume of whole cylinder in x- direction and \( V_{xp} \) is that part of the volume that is removed to form the cruciform.

\[ V_{xc} = \frac{\pi R_x r_x P_x}{P_x P_y P_Z} \]

\[ V_{xp} = \frac{8}{P_x P_y P_Z} \left[ \int_0^{R_y} \int_0^{R_z} r_x \sqrt{1 - \frac{y^2}{R_x^2}} - dx dy + \int_0^{R_x} \int_0^{R_z} r_y \sqrt{1 - \frac{x^2}{R_y^2}} - dx dx \right] \]

Similarly \( V_{zc} \) represents the volume of whole z-filament and \( V_{zp} \) and \( V_{zfp} \) represent the surplus volumes to be removed from the z-filament to enable a perfect fit to form the solid cruciform.

\[ V_{zc} = \frac{\pi R_z r_z P_z}{P_x P_y P_Z} \]

\[ V_{zp} = \frac{8}{P_x P_y P_Z} \left[ \int_0^{R_x} \int_0^{R_z} r_z \sqrt{1 - \frac{x^2}{R_z^2}} - dz dx + \int_0^{R_z} \int_0^{R_x} r_x \sqrt{1 - \frac{z^2}{R_x^2}} - dz dz \right] \]
\[
\bar{V}_{zp} = \frac{8}{P_x P_y P_z} \left[ \frac{r_x}{r_x R_x} \int_{-r_x R_x}^{r_x} \int_{-r_x R_x}^{r_x} \int_{-r_x R_x}^{r_x} R_z \sqrt{1 - \frac{y^2}{r_x^2}} dydxdz + \frac{r_y}{r_y R_y} \int_{-r_y R_y}^{r_y} \int_{-r_y R_y}^{r_y} \int_{-r_y R_y}^{r_y} R_y \sqrt{1 - \frac{z^2}{r_y^2}} dydz \right]
\]

To enable scaling of the results and to simplify the equations, non-dimensional parameters are introduced. Eqs (11-13) represent aspect ratios (radius ratios) of the ellipses in x-, y- and z-directions respectively. Pitch-to-radius ratios are shown in Eqs. (14-16). The values of aspect ratios are not less than 1 and similarly, \( \bar{P}_x, \bar{P}_y, \bar{P}_z \) are always more than or equal to 2.

\[
a_x = \frac{R_x}{r_x} \quad (11) \quad a_y = \frac{R_y}{r_y} \quad (12) \quad a_z = \frac{R_z}{r_z} \quad (13)
\]

\[
\bar{P}_x = \frac{P_x}{R_y} \quad (14) \quad \bar{P}_y = \frac{P_y}{R_x} \quad (15) \quad \bar{P}_z = \frac{P_z}{r_y} \quad (16)
\]

The components of metal fraction shown in Eq. (2) are expressed in terms of non parameters in Eqn's. (17-22).

\[
\bar{V}_{xy} = \frac{\pi}{P_x P_y P_z}
\]

\[
\bar{V}_{yx} = \frac{\pi}{P_y P_z}
\]

\[
\bar{V}_{xp} = \frac{8}{P_x P_y P_z} \left[ \int_0^1 \int_0^1 \sqrt{1 - y^2} dydx + \int_0^1 \int_0^1 \sqrt{1 - x^2} dx dy \right]
\]

\[
\bar{V}_{zc} = \frac{\pi a_y}{P_y P_z a_x a_z}
\]

\[
\bar{V}_{zp} = \frac{8}{P_x P_y P_z} \left[ \int_0^1 \int_0^1 \frac{a_y a_z}{a_x a_z} \sqrt{1 - x^2} dx dz + \int_0^1 \int_0^1 \sqrt{1 - z^2} dx dz \right]
\]

\[
\bar{V}_{zfp} = \frac{8}{P_x P_y P_z} \left[ \int_0^1 \int_0^1 \frac{a_y a_z}{a_x a_z} \sqrt{1 - (y a_x a_z)^2} dy dz + \int_0^1 \int_0^1 \sqrt{1 - z^2} dz dy \right]
\]

To study the effect of adding ellipticity to the filaments, metal fraction is plotted against aspect ratio in Fig. 4. The graph shows 1-\( \varepsilon \) versus aspect ratio at constant pitch-to-major radius ratios, \( P/R= 2, 4, 6 \). In the case shown all the aspect ratios and pitch-to-major radius ratios are considered equal. At aspect ratio, \( a=1 \) the filaments represent...
cylinders with circular cross section. The densest form of solid unit cell is attained at P/R = 2 (a physically realizable limit). The maximum value of metal fraction, 1-ε = 0.942 is shown in Fig. 4. It is observed from the Fig. 4 that metal fraction decreases as aspect ratio increase. Furthermore, there is a decrease in metal fraction as pitch-to-radius ratio increases. Fig. 5 plots metal fraction as a function of ax/ay. This graph represents the effect on the metal fraction of introducing anisotropy to the structure. It is observed that as ax/ay increases or the structure is tending towards isotropy, the metal fraction is decreasing. Note, the endpoints of the curve represent physically realizable limits for the conditions shown in the legend.

B. Specific surface area (β)

Specific surface area (β) is defined as the ratio of the surface area of the solid in the unit cell to the volume of the unit cell.

$$\beta = \frac{S_{Solid}}{P_x P_y P_z}$$

(23)

The calculation of specific surface area employs the same methodology as used for the metal fraction calculation. To model the surface of the structure shown in Fig. 2, the x-, y- and z-direction elliptic cross section filament surfaces, with areas $S_{xc}$, $S_{yc}$ and $S_{zc}$, are considered. Pieces having areas, $S_{xp}$, $S_{yp}$ and $S_{zp}$ are removed so that the remaining surfaces shown in Fig. 6 fit together to form the completely hollow surface shown in Fig. 2. To express the specific surface area in terms of non-dimensional parameters (Eqs. 11-16), the product of β and effective radius, $r_e = \sqrt{R_x R_y}$ is considered where

$$\beta r_e = S_{Tx} + S_{Ty} + S_{Tz}$$

(24)

with

$$S_{Tx} = S_{xc} - S_{xp}$$

(26)

$$S_{Ty} = S_{yc} - S_{yp}$$

(26)

$$S_{Tz} = S_{zc} - S_{zp}$$

(27)

Fig. 4 Metal fraction Vs Aspect ratio

Fig. 5 Effect of anisotropy on Metal fraction
where $S_{Tx}$, $S_{Ty}$, $S_{Tz}$ are the remaining area of the cylinder in $x$-, $y$- and $z$- direction as shown in Fig. 7

$$S_{xc} = \frac{4\sqrt{a_y}}{a_x P_z P_y} \left[ \frac{\pi}{2} \sqrt{\sin^2 \theta + a_x^2 \cos^2 \theta} \right]$$  \hspace{1cm} (28)

$$\begin{align*}
S_{xp} &= \frac{\sqrt{a_y}}{P_x P_y P_z a_x} \left[ \frac{\pi}{2} \sqrt{\sin^2 \theta + a_y^2 \cos^2 \theta} \right] \\
&\quad \left[ \tan^{-1} \left( \frac{a_y}{a_x a_z} \right) \right] \\
&\quad \left[ \int_0^\pi \int_0^{\tan^{-1} \left( \frac{a_y}{a_x a_z} \right)} \sqrt{\sin^2 \theta + a_x^2 \cos^2 \theta} d\theta d\theta \right]
\end{align*}$$  \hspace{1cm} (29)

$$S_{yc} = \frac{4\sqrt{a_y}}{P_z P_y} \left[ \frac{\pi}{2} \sqrt{\sin^2 \theta + \frac{\cos^2 \theta}{a_y^2}} \right]$$  \hspace{1cm} (30)

$$\begin{align*}
S_{yp} &= \frac{\sqrt{a_y}}{P_x P_y P_z} \left[ \tan^{-1} \left( \frac{a_y}{a_x a_z} \right) \cos \theta \right] \\
&\quad \left[ \sqrt{\sin^2 \theta + a_y^2 \cos^2 \theta} \right] \\
&\quad \left[ \int_0^\pi \int_0^{\tan^{-1} \left( \frac{a_y}{a_x a_z} \right)} \sqrt{\sin^2 \theta + a_x^2 \cos^2 \theta} d\theta d\theta \right]
\end{align*}$$  \hspace{1cm} (31)

$$S_{zc} = \frac{4\sqrt{a_y}}{P_x P_y a_x} \left[ \frac{\pi}{2} \sqrt{\sin^2 \theta + \frac{\cos^2 \theta}{a_z^2}} \right]$$  \hspace{1cm} (32)
Figure 7 shows dimensionless specific surface area, $\beta r_e$ plotted against aspect ratio holding metal fraction constant. The three cases considered are $1-\varepsilon = 0.26$, 0.60 and 0.8, and all the aspect ratios and pitch to major radius ratios are considered equal. It is observed from the Fig. 7 that $\beta r_e$ increases with the metal fraction. Adding ellipticity (increasing aspect ratio) also results in an increase in dimensionless specific surface area. Figure 8 shows the effect on $\beta r_e$ of introducing anisotropy to the structure. As the value of $a_x / a_y$ increases $\beta r_e$ decreases and the structure tends toward isotropy $\left(\frac{a_x}{a_y} = 1\right)$.

IV. Numerical modeling

A. Computational Code

The governing equations solved include continuity, constant property, incompressible, no body force Navier-Stokes (N-S) equations and the energy equation. Direct numerical simulations (DNS) using Fluent (version 6.2.16) [10] is used for the numerical simulations. The flow solver is based upon finite volume collocated second order spatial discretization. Second–order central differencing has been used for convective terms. The SIMPLEC algorithm is used to enforce the coupling between the velocity and pressure field and to impose the divergence free condition. A dual time stepping technique is employed to advance the simulations in time. The dual technique consists of an outer and inner loop, where the outer loop is based upon the three-level second-order time advancement, while
the inner iteration uses algebraic solver with a Gauss-Seidel smoother. For each time step 10 inner iterations are used.

B. Computational Domain and Boundary Conditions
Following Gullbrand et al. [8], a single unit cell, shown in Fig. 9, was used to perform the numerical simulations. The “unit cell” assumption reduces the complexity of the problem. It is expected to give a good representation of periodically fully developed flow heat exchange matrix performance. The outer dimensions of the unit cell are \( P_xP_yP_z \). The curved surfaces are fluid-solid interfaces; the elliptical filament surfaces. The plain surfaces represent openings that connect to adjacent cells. Gullbrand et al. studied the flow and thermal characteristics of box lattices with circular cross section filaments. The current case is a more streamlined version of their geometry, where the structure is stretched along the x-direction thereby streamlining the flow through the matrix. The current case has \( a_x = 1, a_y = a_z = 3, \) \( P/R = 3.1 \) and \( \varepsilon = 0.4 \) and \( \beta_{re} = 1.151 \). The coolant flowing through the lattice is water (Pr=7).

The simulations are performed by applying constant mass flow in the x-direction. Periodic boundary conditions are applied in the x-direction to enable global mass conservation. This requires that the mass entering through the inlet plane is same as the mass leaving the outlet plane. Periodic boundary conditions are also applied to the lateral plain surfaces. This enforces mass conservation and also allows the domain to communicate with the surrounding flow cells. Isothermal boundary conditions are applied to the filament surfaces, and periodicity is applied to the plane surfaces (openings). All the flow field simulations start from a zero velocity field and advance in time till they converge to a steady solution. Then this solution is used to calculate the solution to the energy equation.

C. Computational Grid and Convergence Criteria
Computational grids for all cases are generated using Gambit (version 2.2.30). Unstructured grids are generated in regions away from the walls. The near wall regions are treated with fine boundary layer grids to capture the flow behavior. The number of grid elements for all the test cases are constant. To exhibit grid independence two grids with varied grid resolution are used to resolve flow fields for a specific Reynolds number. Friction factors are calculated for the two computational grids. If the difference in values is not greater than 1%, the results are considered grid-converged. Similarly a 10% criterion is applied to the thermal flow field simulations, where the Stanton number is used as variable of convergence.

V. Results

A. Velocity contours
The stream-wise velocity contours for \( Re=150 \) for the elliptic cross section filament box-lattice is shown in Fig. 10; and, the corresponding velocity map of stream-wise velocity in a circular cross section filament box lattice having the same porosity, \( \varepsilon = 0.4 \) and same dimensionless pitch, \( P_x = P_y = P_z = 3.1 \) is shown in Fig. 11. A cross section along the flow direction is shown in the figures. The cross section is centered in the flow domain. The velocities shown are normalized by average pore velocity. The flow is steady and laminar for \( Re= 150 \). The figure shows jet like behavior through the domain. The flow behavior in both the cases is similar. However, the flow in the circular cross section filament lattice is more intense than that found in the elliptic cross section filament lattice.
even though the flow cross sectional area of the circular cross section filament lattice is larger. Furthermore, regions of flow reversal (negative streamwise velocity) are more extensive in the elliptic cross section filament lattice.

B. Friction factors (f)

Friction factors are plotted against Reynolds numbers in Fig. 12. The friction factor is calculated as

\[ f = \frac{\Delta p D_h}{0.5 \rho V^2 P_z} \]

where \( \Delta p / P_z \) is the stream-wise pressure gradient. The case shown has \( a_x = 1, a_y = a_z = 3, P_x = P_y = P_z = 3.1, \varepsilon = 0.4 \) and \( \beta_{re} = 1.15 \). To study the effect of streamlining the filaments on friction factors, the results are compared to cylinders with \( a = 1, P/R = 3.1, \varepsilon = 0.4 \) and \( \beta_{re} = 0.822 \). The results are also compared to flow through 3-D stacked weaves [8] and square channels having the same hydraulic diameter. The friction factors calculated from the numerical simulations for elliptic cross section filaments are close to but slightly higher than those found for flow through circular cross section filament box lattices. The elliptic cross section filaments case also exhibits higher friction factors than those of square channels and 3-D stacked weaves.

C. Stanton numbers (St)

Stanton numbers as a function of Reynolds number are plotted in Fig. 13. The Stanton number is defined as

\[ St = \frac{h}{\rho c v} \]

where \( h = q / \beta P_x P_y P_z (T_s - T_m) \) with \( T_m \) the volume-average fluid temperature. The Stanton numbers of the elliptic cross section filament case are compared to those of circular cross section filament box lattices [8] and 3-d stacked weaves [7]. The elliptic cross section filament box-lattices have significantly higher Stanton numbers when compared to the circular cross section filament case. The Stanton numbers of 3-d weaves are close to the present geometry. The graph also shows that the Stanton numbers decrease with increasing Reynolds numbers.

VI. Conclusions

Analytical models for porosity and specific surface area are developed by considering a single unit cell of the structure. The porosity and specific surface area are shown to depend on six dimensionless parameters: 3 filament cross section aspect ratios \( (a_x = D_x / d_x, \text{ etc.}) \) and 3 pitch – to – radius ratios \( (\bar{P}_x = P_x / R_y) \). The model for porosity shows that adding ellipticity to the filaments results in a decrease of metal fraction; and, introducing anisotropy to the structure increases the metal fraction. The dimensionless specific surface area increases with increasing ellipticity; and, anisotropic structures have higher specific surface area.

Numerical simulations are performed to evaluate the flow and thermal characteristics of elliptic filament box lattices. The unit cell considered is anisotropic with \( a_x = 1, a_y = a_z = 3, P/R = 3.1 \) and \( \varepsilon = 0.4 \) and \( \beta_{re} = 1.161 \). The flows evaluated are laminar in that flows for all the Reynolds numbers considered resulted in steady flow fields. The flows through the matrices exhibited jet like behavior. Friction factors and Stanton numbers are calculated and the results are compared to circular cross section filament lattices, 3-D stacked weaves and square channels. The elliptic filament matrices behaved similar to the circular cross section filament case. The friction factors for both geometries were close. The 3-d stacked weaves and square channels had lower friction factors than the box lattices.
The elliptic filament box lattice Stanton numbers are significantly higher than those of the circular cross section filament lattices, and lower than those of the 3-D stacked weaves.

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