The Kenics static mixer: new data and proposed correlations

P. Joshi a, K.D.P. Nigam a, E. Bruce Nauman b

a Indian Institute of Technology, Delhi, Department of Chemical Engineering, IIT Hauz Khas, New Delhi 110016, India
b Rensselaer Polytechnic Institute, Isermann Department of Chemical Engineering, Troy, NY 12180-3590, USA

Received 14 June 1994; accepted 11 November 1994

Abstract

New results for wall-to-tube heat and mass transfer in a Kenics-type static mixer allow a unification of extent data. Nearly universal correlations are presented. They allow detailed comparisons with open tube designs. Heat transfer enhancement is greatest in deep laminar flow. Even there, the Kenics mixers exhibit modest improvements when compared on the basis of equal pressure drop. Existing designs are not yet optimized for heat transfer and studies at lower aspect ratios for the mixing elements are recommended.

Keywords: Kenics static mixer; Heat transfer; Mass transfer

1. Introduction

The Kenics static mixer was designed to mix comparable liquids without recourse to mechanical motion. The device relies on a systematic splitting, reorientation and recombination of the two fluids using a series of mixing elements. The mixing elements are made from thin, flat strips, twisted through 180° to form helices having aspect ratios (length to diameter) of 1.5–2.5. Helices of alternating left- and right-hand rotations are inserted inside a tube having the same diameter as the mixing elements. The fluids to be mixed are fed into the semicircular passages formed on either side of the first helical element. On meeting the second element, the relatively perpendicular attitude of adjacent forward and rearward edges divides the two separate streams so that a portion of each fluid is fed to the semicircular passages in the second mixing element. This process is repeated at each entry to subsequent elements so that the number of layers at the exit of the array is $2^N$ where $N$ is the number of elements.

The helical inserts cause a secondary flow in the plane perpendicular to the predominant, downstream flow. Compared with an open tube of the same length and diameter, the Kenics mixer gives a substantial enhancement of heat and mass transfer from the surface of the tube to the fluid. This enhancement is greatest in laminar flow but also exists in transition and turbulent flows.

Grace [1] found the following relationship for heat transfer in laminar flow for a Kenics mixer with elements of aspect ratio 1.5:

$$\text{Nu} = 3.65 + 3.8(\text{Re Pr} \frac{D_t}{L})^{1/3}$$

(1)

For turbulent heat transfer, he reports

$$\text{Nu} = 0.075 \text{ Pr}^{-0.4} \text{ Re}^{0.8}$$

(2)

Morris and Misson [2] and Morris and Benyon [3] presented details of local and mean mass transfer from the surface of a tube fitted with Kenics-type elements with aspect ratios of 2.5. Measurements were made on the transfer of naphthalene from the tube surface to air flowing down the tube. They give the following results for mean Sherwood number:

$$\text{Sh}_h = 1.86(1+0.32N)(\text{Re}_h \text{ Sc} \frac{D_h}{L})^{1/3}$$

for $500 < \text{Re}_h < 1600$  (3)

where the subscript $h$ denotes use of the hydraulic mean diameter. For turbulent flow they report

$$\frac{\text{Sh}_h}{\text{Sh}_{oh}} = 1 + 0.06N^{0.288} \text{ Re}_h^{0.32} \text{ Sc}^{-0.4}$$

for $9000 < \text{Re}_h < 30000$  (4)

where the subscript $o$ denotes an open tube:

$$\text{Sh}_o = 0.023 \text{ Sc}^{-0.4} \text{ Re}^{0.8}(1+6D_t/L)$$

for $L/D_t > 20$  (5)

Eq. (5) represents a short tube correction due to Kreith [4]. Note that the mean Sherwood number in Eq. (5) is based on an open tube having the same hydraulic mean diameter as that in the Kenics mixer. Thus, for
Eq. (5), the diameter of the reference tube is smaller than that of the Kenics mixer. The hydraulic mean diameter in a Kenics mixer is approximated by

\[ D_h = \frac{\pi D_s - 4w}{\pi + 2 - 2w/D_s} \]  

(6)

where \( D_s \) is the bore diameter and \( w \) is the thickness of the helical strip. A value of \( w = 0.075D_s \) was used in the present study and is representative of applications where enhancement of heat transfer is important. Thus \( D_h = 0.555D_s \) will be assumed. The mean velocity based on the actual cross-section will be higher than the superficial velocity since the strip reduces available area. With \( w = 0.075D_s \), the factor is \( \tilde{u} = 1.11u_o \).

The enhanced heat and mass transfer possible with the Kenics elements is at least partially offset by increased pressure drop. For elements with \( Ra = 1.5 \) and laminar flow, Grace gives

\[ \frac{\Delta P}{\Delta P_o} = 4.86 + 0.68 \text{ Re}^{0.5} \]  

(7)

where \( \Delta P_o \) is the pressure drop in an open tube with the same length and diameter:

\[ \Delta P_o = \frac{32 \mu \rho L}{D_s^2} \]  

(8)

It should be noted that Eqs. (7) and (8) apply to a Newtonian fluid with constant viscosity. When appreciable heating or cooling occurs, the pressure drop in the open tube and in the Kenics relative to the open tube can be significantly different from those given by Eqs. (7) and (8).

For \( Ra = 2.5 \), Morris and Benyon [3] report

\[ \frac{\Delta P}{\frac{1}{2} \rho \tilde{u}^2 L} = 12.6 \text{ Re}_h^{-0.5} \quad \text{for Re}_h < 6000 \]  

(9)

and

\[ \frac{\Delta P}{\frac{1}{2} \rho \tilde{u}^2 L} = 1.1 \text{ Re}_h^{-0.11} \quad \text{for} \quad 6000 < \text{Re}_h < 30000 \]  

(10)

The above results constitute the existing design equations for tube wall to fluid heat and mass transfer in Kenics-type static mixers. The present study extends the experimental measurements to Reynolds numbers and aspect ratios not included in previous studies. A unified and comprehensive set of correlations is proposed and detailed performance comparisons of the Kenics with an open tube are given.

2. Experimental details

Mass transfer characteristics of the Kenics mixer were evaluated by making local measurements of the transfer of naphthalene from the inner surface of the tube to air flowing down the tube. The methodology generally followed that of Morris and coworkers [2,3].

The test sections were assembled from segments, each fitted with a single helical element inserted into a naphthalene liner which was cast inside a copper tube. The inner bore of the naphthalene liner was 20 mm and each segment was 30 or 40 mm long. The helical mixing elements were made from 1.5 mm thick stainless steel strips which were twisted into helices having 180° left- or right-hand rotations. Segments of alternating rotation were mounted face to face in an allocating cradle to form the test section. Inlet and outlet connections were open, metal tubes with a 20 mm diameter. Pressure tabs were located in the inlet and outlet connections. The design was essentially identical to that of Morris and coworkers [2,3].

Air from a compressor was fed through a metering valve, orifice meter and calming section prior to entering the test section. Exhaust air was vented to the atmosphere. Temperature inside the mixer was measured for each run. Each run lasted 30 min. The extent of naphthalene transfer was determined by weighing each segment at the start and end of a run using a Metler balance having an accuracy of 0.1 mg. The actual loss of naphthalene did not significantly reduce the thickness of the naphthalene liner. Replicate runs confirmed good reproducibility of the data.

Initial tests were conducted with the naphthalene liners but without mixing elements. This enabled comparison with results to the classical Graetz [5] solution. The computation of local and mean Sherwood numbers from the experimental data followed the method of Morris and Misson [2] and Joshi [6]. Agreement between the measured and predicted results was deemed acceptable (Fig. 1).

Fig. 2 shows local Sherwood numbers for several Reynolds numbers using mixing elements with an aspect ratio of 2.0. Qualitatively similar results were obtained for an aspect ratio \( Ra = 1.5 \). After the first two or three elements, the local Sherwood number is nearly independent of axial position. This finding suggests that the flow is transitional or turbulent rather than laminar.

Fig. 3 compares the results obtained here with those for an aspect ratio of 2.5 as obtained by Morris and Misson [2]. The comparison is made at a nearly identical Reynolds number, \( \text{Re}_s \approx 1600 \). The profiles of local Sherwood number vs. number of mixing elements suggest that flow remained laminar for the case of mixing elements with \( Ra = 2.5 \).

Fig. 4 shows the experimental results for the average Sherwood number in a Kenics-type static mixer with 10 elements. Included as data are the results obtained in the present study together with those of Morris and Misson [2] and Morris and Benyon [3]. The new data, reported here, are generally consistent with the earlier
results but are in a transitional range of Reynolds numbers. A correlation of general form

\[ \text{Sh}_{\text{mn}} = A \cdot \text{Re}^a \cdot \text{Sc}^b \cdot N^c \cdot \text{Ra}^d \]  

(11)

was developed where \( A, a, b, c, d \) are constants, \( N \) is the number of elements and \( \text{Ra} \) is the aspect ratio of an element. The solution technique of Johnson [7] was used to obtain

\[ \text{Sh}_{\text{mn}} = 0.045 \cdot \text{Re}^{0.58} \cdot \text{Sc}^{0.05} \cdot N^{0.08} \cdot \text{Ra}^{-0.17} \]  

(12)

This correlation fits the experimental data quite well, generally within 10%. The exponent on \( \text{Re} \), 0.58, falls within the expected range from \( a=0.333 \) for laminar flow to \( a=0.8 \) for turbulent flow. The exponent on \( \text{Sc} \), 3.05, falls outside the expected range from \( b=0.33 \) to \( b=0.40 \). This apparently spurious result is attributed to the small range over which \( \text{Sc} \) was measured. The exponent on \( N \), 0.08, exhibits a weak but anomalously positive \( L/D \) effect. However, as seen from the measurements of local Sherwood number shown in Fig. 3, the positive exponent is due to the first one or two elements and \( c \approx 0 \) for \( N > 2 \). The observed coefficient on \( \text{Ra} \), \( -0.71 \), is consistent with the observation (e.g., see Dackson and Nauman [8]) that mixing in a Kenics mixer is improved at low aspect ratios. Proposed modifications to Eq. (12) are discussed in the next section.

Fig. 5 shows the flow resistance characteristics of a Kenics mixer with \( N=10 \). Morris and Misson [2] found the friction factor to be independent of \( N \). The following correlation fits the present experimental results within 10%:

\[ f = \frac{\Delta P}{\frac{1}{2} \rho U^2} \frac{D_b}{L} = 30.3 \cdot \text{Re}_{\text{h}}^{-0.488} \cdot \text{Ra}^{-1.04} \]  

(13)
For $\alpha = 2.5$, Eq. (13) agrees closely with the Morris and Misson [2] result (Eq. (9)).

3. Recommended correlations

The practical utility of the results presented here is to estimate wall-to-fluid fluid heat transfer coefficients in tubes equipped with Kenics static mixers. The mass transfer measurements have little direct use: few processes involve the sublimation of a solid from the inside of a tube. In recognition of these facts, we attempt to recast the results in forms most useful for heat transfer calculations.

The published studies [1–3] and the new data presented here are remarkably consistent. Fig. 5 displays
the results from the three studies with Pr (or Sc) = 2.55 and $N = 10$. The aspect ratio factor $Ra^{-0.71}$ reconciles the data quite well. For general use, however, it is necessary to modify the published correlations. At very low values of $Re Pr D_i/L$, Nu (and Sh) approach asymptotic values corresponding to a fully developed boundary layer. It is tempting to use the form of Grace (Eq. (1)). However, Grace apparently expected a tube filled with kinetic elements to approach the same limit, $Nu = 3.65$, as for an open tube. There is no reason to expect this and Grace’s experimental range was not sufficient to justify an extra, fitted parameter. Thus, following Morris and coworkers, we choose a Seider–Tate form [9] even though it is known to underestimate Nu substantially at low values of $Re Pr D_i/L$.

Morris and coworkers believed that their correlations should become equivalent to open tube results in the limit of $N = 0$ and contrived functional forms to ensure this. Their attempt seems misguided since $N$ and $L/d$ are proportional, and the limit of zero tube length holds little interest. Instead, it is desired that the correlations hold for fairly long tubes filled with mixing elements since most applications take this form. The correlations of Morris and coworkers show Nu to increase to arbitrarily large values as tube length increases. For laminar flow, Nu should vary as $(D_i/L)^{1/3}$, and Nu should be approximately independent of Nu for turbulent flow.

We also choose to use the open tube diameter rather than the hydraulic mean diameter. The factors $D_h = 0.555$ and $u* = 1.11u_*$ were assumed in the following recommended correlations: for $Re < 700$,

$$Nu = 6.1(Re Pr D_i/L)^{1/3} Re^{-0.71}$$ for $700 < Re < 1000$,  
$$Nu = 0.46 Re^{0.58} Pr^{0.4} Ra^{-0.71}$$

for $Re > 1000$,

$$Nu = 0.1 Pr^{0.4} Re^{0.8} Ra^{-0.71}$$

The somewhat arbitrary division between the laminar, transitional, and turbulent regimes were determined by matching predicted values for Nu. The match between Eqs. (14) and (15) assumed $Pr = 2.55$, $L/D_i = 15$. The match is imperfect at other values of $L/D_i$.

For laminar flow, Grace’s equation for pressure drop was modified to reflect the dependence on Ra found in the present study. For higher Reynolds numbers, Eq. (13) was adjusted to use the nominal diameter rather than the hydraulic mean diameter. For $Re < 700$,

$$\Delta P \over \Delta P_o = (7.41 + 1.04 Re^{0.5}) Ra^{-1.04}$$

The choice of $Re = 700$ for the switching point between Eqs. (17) and (17) reflects their experimental ranges and is consistent with the switching points between Eqs. (15) and (16). In fact, Eq. (17) predicts higher pressure drops out to $Re \approx 2500$, but the difference is small.

4. Performance comparisons

The comprehensive set of design equations allows comparisons between different aspect ratios and with an open tube. The comparisons all involve heat transfer to a fluid with constant physical properties which is fed to the various systems at the same rate. Heat transfer in the open tube in laminar flow is governed by the Seider–Tate [9] equation

$$Nu = 1.86(Re Pr D_i/L)^{1/3}$$ for $Re < 2100$

while Eq. (5) applies to turbulent flow. For pressure drop, Eq. (8) is used for laminar flow and

$$\Delta P \over \rho d L = 0.316 Re^{-0.25}$$ for $Re > 2100$

for turbulent flow.

Table 1 compares the Kenics with an open tube having the same length and diameter. In this simple retrofit case, heat transfer is improved but at the expense of a substantially higher pressure drop. The performance enhancement is roughly independent of Reynolds number, but the extra pressure drop increases sharply with Reynolds number. Note that the residence time is lower with the Kenics: $t = 0.9t_{open}$.

The pressure drop can be decreased by the simple expedient of shortening the tube. In laminar flow, there will be an increase in Nu and thus in heat transfer coefficient $h$, but the loss in surface area greatly exceeds the gain in $h$ so that the product $hA$ sharply decreases in the shortened retrofit case.
Table 1
Comparison of a Kenics mixer with an open tube for the retrofit case (Pr = 2.55, L/Ds = 15)

<table>
<thead>
<tr>
<th>Ra</th>
<th>Re</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>hA/(hA)open</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.7</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>ΔP/ΔPopen</td>
<td>5.5</td>
<td>7.7</td>
<td>11.7</td>
<td>24.4</td>
<td>16.0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ra</th>
<th>Re</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>hA/(hA)open</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.2</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>ΔP/ΔPopen</td>
<td>4.1</td>
<td>5.2</td>
<td>8.7</td>
<td>18.1</td>
<td>11.9</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ra</th>
<th>Re</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>hA/(hA)open</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.9</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>ΔP/ΔPopen</td>
<td>3.3</td>
<td>4.1</td>
<td>6.9</td>
<td>14.3</td>
<td>9.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
Comparison of a Kenics mixer with an open tube for the initial design case with volumetric flow rate, residence time and pressure drop held constant (Pr = 2.55, (L/D)open = 15)

<table>
<thead>
<tr>
<th>Ra</th>
<th>(Re)open</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>hA/(hA)open</td>
<td>1.8</td>
<td>1.7</td>
<td>1.5</td>
<td>1.3</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Ds/Dopen</td>
<td>1.35</td>
<td>1.40</td>
<td>1.50</td>
<td>1.70</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>L/Lopen</td>
<td>0.61</td>
<td>0.57</td>
<td>0.49</td>
<td>0.38</td>
<td>0.46</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ra</th>
<th>(Re)open</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>hA/(hA)open</td>
<td>1.5</td>
<td>1.5</td>
<td>1.3</td>
<td>1.1</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Ds/Dopen</td>
<td>1.29</td>
<td>1.33</td>
<td>1.43</td>
<td>1.62</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>L/Lopen</td>
<td>0.67</td>
<td>0.63</td>
<td>0.54</td>
<td>0.42</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ra</th>
<th>(Re)open</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>hA/(hA)open</td>
<td>1.4</td>
<td>1.3</td>
<td>1.2</td>
<td>1.0</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Ds/Dopen</td>
<td>1.24</td>
<td>1.28</td>
<td>1.38</td>
<td>1.56</td>
<td>1.43</td>
<td></td>
</tr>
<tr>
<td>L/Lopen</td>
<td>0.72</td>
<td>0.68</td>
<td>0.58</td>
<td>0.46</td>
<td>0.54</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 shows performance comparisons for an initial design case where volumetric flow rate, mean residence time and pressure drop are held constant. The design with the Kenics uses a larger D, and shorter L than the open tube. It does provide a significant increase in hA at low Reynolds numbers and, for this initial design case, the Kenics elements with Ra = 1.5 are clearly preferred. The improvements in hA decrease sharply with increasing Reynolds number, and the open tube becomes better in turbulent flow.

5. Conclusions

Presented here are comprehensive correlations for tube-to-wall heat or mass transfer coefficients for the Kenics static mixer. Previous literature results are quite consistent with the new results given here when reconciled with a correction factor for aspect ratio. Thus the proposed correlation should be adequate for design purposes when used within the range of experimental verification. The overall range on Re is from 0.1 to 50,000. Most of the experiments used air with Sc = 2.55, but Grace [1] also used a variety of liquids. As presented here, the correlations are limited to mixers with N > 3. The upper limit on N is at least 10 and is presumably much higher. The experimental range on Re Pr Ds/L in the laminar regime is from 20 to 3000. Note, however, that the correlations exhibit typical dependences on Re Pr Ds/L or Pr and thus can be expected to hold for ordinary fluids if not for unusual fluids such as liquid metals and superfluid helium. The experimental range on Ra is 1.5–2.5.

In most process applications, the Kenics elements are metal and fit snugly within a metal tube. This may give an extended area or fin effect which is not reflected in the mass transfer results of Morris and coworkers [2,3] or here. However, it was presumably included in Grace’s [1] measurements and is thus believed to be small.

The Kenics elements give a modest improvement in hA when considered as part of an initial design. The best case shown is an 80% improvement at low Reynolds numbers using the elements with Ra = 1.5. Considerations of capital cost and difficulty of cleaning suggest that these mixers would be useful to enhance heat transfer in only a few, critical applications. Of course, the mixing action of the Kenics may perform other useful functions.

The mixers with the lowest aspect ratio performed best. The functional forms used for the aspect ratio correction give no optimal Ra within the experimental range but suggest that still shorter Ra should be explored.

The results presented here are confined to one particular and very simple type of static mixer. Other, more complicated designs exist and may exhibit significantly better results. Also, further improvements, even of the Kenics design, can be expected. These mixers have proven utility in blending miscible fluids, and, sometimes, in dispersion of immiscible fluids. It may also be that they will also evolve into efficient enhancers of heat transfer.

Appendix A: Nomenclature

Roman symbols

- C: total molar concentration
- Cp: heat capacity of fluid
- D: diffusivity of fluid
- Ds: hydraulic mean diameter of mixer (Eq. (6))
- D: diameter of tube
- f: friction factor (Eq. (13))
- h: heat transfer coefficient based on inside area of tube
\begin{align*}
k & \quad \text{thermal conductivity of fluid} \\
K & \quad \text{mass transfer coefficients based on inside of tube} \\
L & \quad \text{length of tube} \\
N & \quad \text{number of mixing elements} \\
Nu & \quad \frac{dD_c}{k}, \text{ Nusselt number} \\
\Delta P & \quad \text{pressure drop across mixer} \\
\Delta P_o & \quad \text{pressure drop for open tube} \\
Ra & \quad \text{length-to-diameter ratio for a mixing element} \\
Re & \quad \frac{\rho D_c u}{\mu}, \text{ Reynolds number} \\
Re_h & \quad \frac{\rho D_c \bar{u}}{\mu}, \text{ Reynolds number based on hydraulic mean diameter} \\
\Pr & \quad C_p \mu k, \text{ Prandtl number} \\
Sh & \quad \frac{K D_c}{c D}, \text{ Sherwood number} \\
Sh_h & \quad \frac{K D_c}{c D}, \text{ Sherwood number based on hydraulic mean diameter} \\
Sh_o & \quad \text{Sherwood number for an open tube} \\
Sh_{mn} & \quad \text{mean Sherwood number for series of mixing elements} \\
\bar{u} & \quad \text{average velocity of fluid} \\
u_o & \quad \text{velocity in open tube} \\
Sc & \quad \frac{\rho D}{\mu}, \text{ Schmidt number}
\end{align*}

\textbf{Greek symbols}

\begin{align*}
\mu & \quad \text{viscosity of fluid} \\
\rho & \quad \text{density of fluid}
\end{align*}

\textbf{References}