DEPOSIT FORMATION AND MITIGATION IN AIRCRAFT FUELS

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ABSTRACT
The development of a viable strategy for limiting coke deposition involves combining synergistic approaches for suppressing deposit buildup and reducing its impact on performance. Candidate approaches, including selection of favorable operating conditions (viz., pressure, temperature, heat flux, residence time and passage size) and coke-tolerant heat exchanger designs, were investigated to evaluate their effectiveness and provide a basis for combining them into a single design philosophy. These approaches were evaluated through testing of current jet fuels in single-tubes and segments of heat exchanger configurations at temperatures up to 1000 F, pressures up to 1200 psi and liquid hourly space velocities up to 40,000/h.

A key result of this work is the ranking of the importance of heat exchanger operating conditions on carbon deposition, with fuel temperature and those parameters that control species diffusion having the most pronounced impact. Residence time and pressure are of lesser importance. Alternative coke-tolerant heat exchanger designs featuring inter-channel communication were evaluated and ranked, with several of these concepts demonstrating improvement over continuous passages.

INTRODUCTION
High heat sink fuel cooling technology can be applied to enhance engine performance over the entire spectrum of flight regimes. For hypersonic flight, it provides the only means for meeting the cooling requirements with storable fuels; for advanced fighter aircraft, it provides a path to enhance performance with current materials; and, for lower-speed-military and commercial aircraft, it can increase growth potential and play a key role in emissions-reduction strategies. However, utilization of this technology will require heating the fuel to supercritical temperatures — well above the maximum temperature (~325 F) allowable in conventional fuel systems.

The principal engine operability issue that will affect hydrocarbon fuel cooling technology is coke formation. In gas turbine applications, where long duty cycles are required, even low rates of deposition will accumulate, degrading performance and, if left unchecked, leading to system failure. In hypersonic missile applications, duty cycles are short, but requirements for maximizing heat sink lead to very high fuel temperature operation and the potential for accelerated coking. The extent to which the benefits of this technology can be realized is directly related to our ability to mitigate against coke formation.

The objective of this study is to investigate coke deposition in aircraft fuels and to identify design concepts for minimizing its impact. Candidate approaches were investigated to evaluate their effectiveness and provide a basis for combining them into a single design philosophy. The individual elements examined include: (1) Definition of guidelines for specifying operating conditions to minimize coke deposition in both the subcritical and supercritical temperature regimes, and (2) Identification and evaluation of heat exchanger design concepts that have the potential for accommodating moderate coke buildup without progressive degradation.

The key variables and component operating conditions examined correspond to gas turbine and scramjet applications. Tests were conducted using Jet A and JP-8 fuels that were supplied by the Air Force Research Laboratory (batches POSF-2926 and -3405, respectively) and with JP-8+100, which includes special thermal stability additives. The test results can be used to define guidelines to support fuel heat-exchanger/thermal management system design and implementation, as well as to broaden the database available for validating and upgrading coke deposition models.

BACKGROUND
In the temperature regime below approximately 700 F, oxygen dissolved in fuel is the major contributor to thermal decomposition and coke deposition. When air-saturated fuel is heated to temperatures above approximately 350 F, the dissolved oxygen reacts to form free-radical species (coke precursors) which initiate and propagate other autoxidation reactions leading to deposit formation. These reaction paths are dominant at temperatures up to approximately 700 F.

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but become insignificant when the concentration of the dissolved oxygen is reduced from its saturated value (70 ppm) to very low levels (<5 ppm). It has been shown that the dissolved oxygen is consumed as coke deposit is formed, and that increasing fuel temperature within the autoxidation regime accelerates oxygen depletion (Balster and Jones, 1997).

At temperatures above approximately 800°F, the deposition mechanism is characterized by pyrolysis, wherein chemical bonds are broken and large alkanes are converted into smaller alkanes, alkenes, and some hydrogen. This mechanism for coke production can be initiated by thermal (homogeneous) and/or catalytic (heterogeneous) cracking reactions, and followed by polymerization.

The rate of coke deposit buildup with increasing temperature is illustrated in Fig. 1 for a typical jet fuel. As indicated in the figure, fuel deoxygenation reduces coke deposition at low and intermediate temperatures. At higher temperatures, deposit buildup from aerated fuel approaches deposit buildup from deoxygenated fuel because the dissolved oxygen is consumed and the coke precursors are decomposed (Hazlett, 1991).

TEST APPARATUS

Most of the testing was performed with the Multiple Heated-Tube Coking Rig shown in Fig. 2. The individual tubes were manufactured from type 304 stainless steel and sized to simulate single passages in a heat exchanger. The parallel flow paths enable simultaneous evaluation of up to five configurations that may have different geometries or operating conditions, and are particularly efficient for long-duration testing. A nearly uniform surface temperature distribution is obtained by clamping the tubes between isothermal copper blocks (8-in. x 8-in. x 1-in.) that are heated electrically by strip heaters attached to the outer surface. In some tests, coupons consisting of multiple flow passages were used.

Prior to a test, 1.5-gal piston-type accumulators are filled with fuel by a gear pump. The 1.5-gal capacity allows a full day of testing at moderate flow rates. Longer/higher flow-rate tests can be accommodated by refilling fuel on-line, during tests. By applying high-pressure nitrogen to the back-side of the pistons in the accumulators, the fuel is then pressurized to 150 to 200 psig higher than the predetermined test pressures. The five flowpaths are essentially independent; the construction of the rig requires only that the test sections operate at the same back-pressure. The flowpaths may have different fuels, flow rates, additives, coatings, and/or tube sizes. In each of the separate flowpaths, the fuel is filtered and the flow rate is measured by a flowmeter and controlled by a metering valve. Depending on the desired simulation conditions, the fuel can be preheated up to about 350°F, which is below its autoxidative coke deposition temperature, before entering the first of two successive test sections. The test sections can be maintained at different temperatures (up to approximately 1200°F), simulating different parts of a thermal management system. Downstream of the heat exchanger tubes, the processed fuel can be sampled for compositional analysis and is quenched in a cooler. System pressure is maintained by a back-pressure regulator.

During a test, key measurements include the inlet and exit fuel temperatures and pressures, and copper block and heat exchanger wall temperatures. These measurements provide important information to correlate performance and coke deposition. In preparation for determining the time-averaged carbon deposition rate, the heat exchanger tube is removed from the rig at the test completion, rinsed with hexane and dried in a vacuum oven. The tubes are then cut into 1½ - 2-in. lengths and the carbon accumulated in each section is determined using a LECO RC-412 Carbon Determinator which quantifies carbon deposition (precision of ± 3%) by measuring carbon dioxide produced.

![Figure 1: Deposition Rate for Jet Fuel](image1)

![Figure 2: Multiple Heated-Tube Coking Rig](image2)
in a controlled carbon burn-off. Typically, the deposit consists of more than 75 percent carbon, with the remainder being oxygen and hydrogen. For the most part, test results are correlated using the total carbon deposit in the tube, i.e., the sum of the individual sections. However, the axial profiles are also examined to explain local phenomena.

**OPERATING CONDITIONS**

The range of parameters investigated was selected to reflect that suitable for practical heat exchanger systems and is summarized in Table 1. Because the flow passages are small, fuel temperatures were measured only at the inlet, the midpoint (between the first and second heated copper blocks), and the exit of the tubes. Fuel temperature profiles were calculated between the measured values based on a uniform surface temperature within each block and heat transfer coefficients determined using the Dittus-Boelter correlation. In the analysis, the complex jet fuel composition is simulated by a mixture of 12 hydrocarbons (Heneghan, et al., 1993) and the physical properties of the mixture at various temperatures and pressures are estimated using the NIST SUPERKAPP program (Ely and Huber, 1990). A representative fuel temperature profile in successive heat exchanger tubes is shown in Fig. 3.

**Table 1: Test Conditions**

<table>
<thead>
<tr>
<th>Key Variables</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>JP-8-100</td>
</tr>
<tr>
<td>Temperature, F</td>
<td>300 - 1000</td>
</tr>
<tr>
<td>Flow rate, lbm/h</td>
<td>1.8 - 7.1</td>
</tr>
<tr>
<td>Tube ID, in.</td>
<td>0.03, 0.058, 0.085</td>
</tr>
<tr>
<td>Pressure, psig</td>
<td>600, 1200</td>
</tr>
<tr>
<td>( \text{IHSV} ), 1/h</td>
<td>860 - 9200</td>
</tr>
<tr>
<td>Residence time, s</td>
<td>0.14 - 1.40</td>
</tr>
<tr>
<td>Test duration, h</td>
<td>7 - 25</td>
</tr>
<tr>
<td>Tube material</td>
<td>stainless steel - 304</td>
</tr>
</tbody>
</table>

*\( \text{IHSV} = \text{volumetric flow rate per tube volume} \)

**Fuel Temperature**

Representative coke deposit levels as a function of fuel temperature are plotted in Fig. 4. The data are correlated in terms of parts-per-million (ppm) of carbon deposit relative to fuel flow (i.e., \( \text{mass}_{\text{carbon}} / \text{mass}_{\text{fuel}} \)) and normalized by surface area for each of the two-inch segments analyzed in the LECO Carbon Determinator. As shown in the figure, the carbon deposition rate increases with increasing fuel temperature up to a point (~600 F) beyond which any further increase in fuel temperature causes the deposition rate to decline. As discussed earlier, the coke deposition over this temperature range comes from the reaction of oxygen dissolved in the jet fuel. The oxidation rate of the fuel is accelerated by increasing the fuel temperature, thereby, increasing the coke deposition rate. However, as the reaction proceeds along the heat exchanger tube, dissolved oxygen is consumed and its concentration decreases. In addition, the decomposition of coke-precursors is also accelerated by increasing fuel temperature. Thus, the depletion of both dissolved oxygen and coke-precursors results in the decreasing rate of deposition.

**Reynolds Number and Passage Size**

Both heat and mass transfer rates are dependent on Reynolds number (Re). The influence on coke deposition of a change in Reynolds number and flow passage diameter at constant flowrate is shown in Fig. 5 in terms of total accumulated carbon. The results indicate that increasing the passage diameter (i.e., decreasing Re) reduces carbon deposition, a trend that has also been reported by Chin and Lefebvre, 1993 and Jones, et al., 1996. Moreover, if the results were normalized by surface area, the effect of passage size on the deposition would be even more pronounced. The trend of decreasing deposit rate with increasing diameter reflects a balance of mass-diffusion length scale, turbulence-enhanced mass-diffusion rates and residence time influences. When air-saturated fuel is heated to temperatures above approximately 350 F, the dissolved oxygen reacts to form free-radical species (coke precursors) which participate in other autoxidation reactions leading to deposit formation. The surface deposition mechanisms are inextricably tied to the mass transfer process. For example, the surface deposition mechanisms

\[
\text{Fuel} + \text{O}_2 \rightarrow \text{Deposit} \\
\text{Precursor} \rightarrow \text{Deposit} \\
\text{Deposit}_{\text{bulk}} \rightarrow \text{Deposit}
\]
involve diffusion of dissolved oxygen, coke precursor, and deposit formed in the bulk flow to the wall surface. The mass transfer length scale, i.e., the mean distance between molecules and the wall surface, is linearly proportional to the passage diameter, and shorter length scales facilitate diffusion. Turbulence of the fuel flow is also affected by the passage size. Smaller ID tubes have larger Reynolds numbers (i.e., Re = 4π/μΔρ) and therefore higher mass transfer coefficients, also promoting diffusion and thereby deposition. As Reynolds number is increased, heat transfer coefficients also increase. Deposition at very high heating rates is discussed below.

### Residence Time and Space Velocity

Increasing the residence time of fuel in the heat exchanger tubes would be expected to increase coke deposition. For this reason, a smaller diameter tube would be expected to give less coke deposition than a larger diameter tube with the same flow rate. However, as discussed above, diffusion is the controlling factor for autoxidative coke deposition at the conditions tested. The influence of the fuel flow rate on the autoxidative coke deposition is shown in Fig. 6. Carbon deposition results are normalized by the fuel flow rate and indicate that, for a constant fuel outlet temperature, carbon deposition increases with increasing flow rate. The mean Reynolds numbers (calculated based on film temperature) and residence times in the heated tubes at the three fuel flow rates plotted are also shown in the figure. As can be seen, although residence time was reduced 50 percent by increasing the flow rate, the deposition doubled. From this and the discussion above, it can be concluded that the enhanced diffusion effect is stronger than the impact of residence time.

To isolate the influence of residence time at a constant Reynolds number, results from two tests were compared, namely, a high fuel flow rate in a large-diameter tube (3.5 lbm/h, 0.058-in. ID, Fig. 5) and a low fuel flow rate in a small-diameter tube (1.8 lbm/h, 0.030-in. ID, Fig. 6). As the Reynolds numbers are equivalent (i.e., Re = 6800) and the carbon deposits were approximately equal in the two tubes, the comparison indicates a balance between the smaller diameter (length scale) tending to increase deposition and the larger diameter (high residence time) tending to decrease deposition. Also, the axial location of the peak deposit was shifted downstream to higher temperature in the smaller-diameter tube, reflecting the effect of reaction kinetics on deposition.

### Pressure

The influence of the fuel pressure on autoxidative coke deposition was investigated using a 0.085-in.-ID tube that was 18-in. long. At pressures of 600 and 1200 psig, 3.5 lbm/h fuel flow and 810 F fuel outlet temperature, the total cumulative carbon depositions were rela-

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**Figure 5: Effect of Passage Size on Deposition**

**Figure 6: Effect of Flow Rate on Deposition**

**Figure 7: Effect of Space Velocity on Deposition**
Test Rig described in Sobel and Spadaccini, 1997. (These high heat resistively heated tubes in the single-element Bench-Scale Reactor cal vapor, increasing pressure will increase residence time and pyro-
coke deposition. At higher temperatures, where the fuel is a supercriti-
pressure in the liquid range has a minor impact on the autoxidative
should have only a small effect on mass transfer and residence time at
of increases in fuel viscosity and density. Therefore, fuel pressure
only a very small decrease in the Reynolds number, as a consequence
the tube, increasing the fuel pressure from 600 to 1200 psig effects

In these tests, the fuel was not preheated upstream of the tube.
given power input, while avoiding excessive end effects and main-
were selected to maximize the heat flux, by reducing wetted area at a
generations for coke-tolerant designs, i.e., designs which have the potential
for accommodating moderate coking rates without progressive degra-
dation, were identified, fabricated as sectors and tested in the
Multi-Tube Coking Rig. Concepts were evaluated that allow for inter-
channel communication, permitting isolation of coke buildup and
thereby coke accommodation, and enhanced heat transfer, due to tur-
bulence generation and frequent restarting of the boundary layer.

A standard test element design, shown in Fig. 9, was developed
and five different fluid passage geometries were created by machining
or chemical milling type 304 stainless steel. Although chemical etch-
ing increases surface roughness (from ~0.4 μm to ~4.0 μm) which can
promote deposition (by increasing surface area or turbulence), the
effect is greatly reduced or eliminated as deposits accumulate (Bradley
for a specific fuel heat sink (heat sink/mass)_fuel). These results show that
carbon deposition can be reduced by significantly increasing heat flux,
while increasing flow rate (and Reynolds number) and decreasing the
residence time. This trend reflects the changing balance between
heating, mixing and kinetics, and occurs in spite of the higher wall
temperatures associated with the higher heat flux. As heat flux is in-
creased substantially with the same fuel exit temperature, the wall
temperature will also increase. At heat fluxes of 45 and 240 Btu/ft²-s,
the exit (peak) wall temperatures were 1200 and 1450 F, respectively
- well into the pyrolytic regime. (The carbon distribution indicates
approximately equal amounts of autoxidative and pyrolytic deposi-
)

Coke-Tolerant Designs
Understanding the impact of operating conditions on deposit
formation enables effective flow passage design. Conventional heat
exchanger designs, whether co-, counter- or cross-flow, are character-
ized by individual parallel fuel passages. In this type of design, carbon
deposits may build up over time, causing a restriction in a given pas-
sage. The restriction, in turn, can reduce the coolant flow in that pas-
sage, increasing local surface and fuel temperatures and thereby poten-
tially increasing the coking rate itself. Moreover, the increased
surface temperature will also result in higher temperatures in neigh-
boring passages and the fouling problem may propagate across the
heat exchanger, resulting in failure. Therefore, candidate configura-
tions for coke-tolerant designs, i.e., designs which have the potential
for accommodating moderate coking rates without progressive degra-
dation, were identified, fabricated as sectors and tested in the
Multi-Tube Coking Rig. Concepts were evaluated that allow for inter-
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promote deposition (by increasing surface area or turbulence), the
effect is greatly reduced or eliminated as deposits accumulate (Bradley

High Heating Rate
To determine the coking characteristics under very high heat flux
and low residence time conditions, a series of tests was performed with
resistively heated tubes in the single-element Bench-Scale Reactor
Test Rig described in Sobel and Spadaccini, 1997. (These high heat
fluxes cannot be achieved over a substantial length of the tube using the
Multiple-Heated Tube Coking rig.) In the single-element Bench-Scale Reactor Test rig, the heat flux is uniform and the wall
temperature increases from inlet to exit (typically from 800 F, to 1400
F). The resistively heated tubes were 12-in. long and 0.030-in. ID, and
were selected to maximize the heat flux, by reducing wetted area at a
given power input, while avoiding excessive end effects and main-
taining readily manageable flow rates with substantial residence times.
In these tests, the fuel was not preheated upstream of the tube.

Tests were run with heat fluxes from 45 to 240 Btu/ft²-s at 600
psi for a duration of 7 hours (one run day). For each test, the fuel exit
temperature was maintained at 1000 F and both autoxidative and py-
rolytic coke was formed. It should be noted that the space velocity
increases by a factor of approximately six over the range of flow con-
titions examined; the residence time is reduced by essentially the same
factor (from 0.4 to 0.07 s).

The carbon deposition results are shown in Fig. 8. Since the tests
were run with the same outlet temperature but different flow rates, this
analysis allows a direct comparison of the amount of carbon deposited

<table>
<thead>
<tr>
<th>Heat flux, Btu/ft²-s</th>
<th>Carbon deposition, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.062</td>
</tr>
<tr>
<td>100</td>
<td>0.050</td>
</tr>
<tr>
<td>200</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8: Effect of Heat Flux on Deposition
et al., 1974). As shown in the figure, the overall size of all coupons was 8.0-in. x 0.55-in. x 0.25-in. The internal patterns were as follows: (1) **Parallel channels** — four 0.050-in. x 0.050-in. straight flow channels separated by 0.025-in. ribs; (2) **Offset parallel strip fins** — same as above, except that the ribs had 0.100-in.-long staggered openings cross-connecting the channels each 1.00-in. along the length; (3) **Circular pin fins** — 0.010-in.-dia. x 0.030-in.-high fins in a 0.045-in. x 0.067-in. staggered grid array; (4) **Small teardrop pin fins** — 0.010-in. x 0.030-in. teardrop fins, 0.030-in. high, in a 0.033-in.- x 0.120-in. staggered grid array; and (5) **Large teardrop pin fins** — 0.010-in. x 0.090-in. teardrop fins, 0.030-in. high, in a 0.033-in. x 0.352-in. staggered grid array. Additional key geometric parameters of the test elements are summarized in Table 2. The same parameters for three cylindrical tubes are also listed in the table for comparison. The differences in these parameters can have significant effects on the heat transfer (i.e., the transverse temperature gradient) and coke deposition. The open volumes of all of the test elements listed in the table are quite similar; therefore, the mean linear flow velocity of fuel through the coupon and the fuel pressure drop should be comparable for the same mass flow rate.

Tests were conducted using JP-8 fuel instead of JP-8+100 to accelerate coke deposition and, thereby, reduce the test time required to evaluate the design concepts. A 0.058-in.-ID tubular preheater was installed in the first copper block (to raise the fuel inlet temperature to 420 F) and the second copper block, containing the test elements, was heated to 1150 F. The tests were run until the fuel pressure drop across the test element increased significantly, indicating that complete blockage was imminent. Since the coke deposit buildup introduced an additional thermal resistance at the wall, causing the fuel temperature to decrease as the tests proceed, the fuel exit temperatures were time-averaged.

Carbon deposit profiles for the large-teardrop pin-fin sector aligned in two different directions of flow are shown in Fig. 10. The data correspond to sixteen 1/4-in. segments of the test element. Reversing the orientation (i.e., flow from the sharp end of the teardrop to the blunt end) facilitates evaluation of the effects of recirculation and turbulence. More carbon deposit was found with the fuel flow direction from sharp-end to blunt-end, which produces a larger and more turbulent wake flow. To reduce the coke deposition, the fuel flow direction should be arranged from blunt-end to sharp-end for the teardrop pin fins. Consequently, only fuel flow from blunt-end to sharp-end was tested for the small teardrop element.

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**Table 2: Test Element Geometric Patterns**

<table>
<thead>
<tr>
<th>Coupon Type</th>
<th>No. of Pins</th>
<th>(V_{\text{flow}})</th>
<th>(A_{\text{surface}})</th>
<th>(\sqrt{A})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel channels</td>
<td>-</td>
<td>0.0706</td>
<td>5.63</td>
<td>80</td>
</tr>
<tr>
<td>Offset strip fins</td>
<td>-</td>
<td>0.0715</td>
<td>5.63</td>
<td>79</td>
</tr>
<tr>
<td>Circular pin fins</td>
<td>1586</td>
<td>0.0745</td>
<td>6.87</td>
<td>92</td>
</tr>
<tr>
<td>Small teardrop pin fins</td>
<td>1155</td>
<td>0.0725</td>
<td>8.06</td>
<td>111</td>
</tr>
<tr>
<td>Large teardrop pin fins</td>
<td>394</td>
<td>0.0727</td>
<td>7.64</td>
<td>105</td>
</tr>
</tbody>
</table>

**Figure 10: Deposit Profiles in Large-Teardrop Pin Fins**

Carbon deposit profiles from tests with each of the five different fuel passages are compared in Fig. 11. Despite the differences in geometry, carbon deposition always peaks at an axial position corresponding to a fuel temperature of 550-650 F. This behavior is consistent with cylindrical tubes and is due to the consumption of dissolved oxygen and coke precursors. The test data, consisting of total carbon deposit, maximum carbon deposit rate and pressure loss, indicate that the order of increasing coke deposition for these designs is:

- Large Teardrop with flow from blunt-end to sharp-end
- Large Teardrop with flow from sharp-end to blunt-end
- Parallel Channels
- Offset Parallel Strip Fins
- Circular Pin Fins ± Small Teardrop with flow from blunt-end to sharp-end

Fuel passage configuration and pin-fin geometric size can significantly impact both the autoxidative coke deposition and heat transfer. In general, for a given shape, the more turbulent configurations enhance heat transfer, but yield more coke deposit as a result of the increased mass transfer. Also, because the fins can provide higher surface area, they can increase heat transfer, thereby increasing the bulk...
fuel temperature and simultaneously reducing the wall temperature. The best configuration of the five designs tested is the large teardrop pin fins with the fuel flow direction from blunt-end to sharp end, as it afforded the longest duration test, smallest coke deposition, and significant heat transfer enhancement.

CONCLUDING REMARKS
The rate of coke deposition results from a balance among the controlling chemical kinetics rates, the fuel residence time and the diffusion rate of reactants and products to the surface. In turn, the kinetics rates are dependent primarily on fuel temperature. Based on the results of the current research, the following conclusions may be made regarding coke deposition/mitigation and guidelines for the design of heat exchangers for gas turbine and hypersonic applications.

- Temperature is the most important factor affecting coke deposition formation. Autoxidative deposition peaks at approximately 600°F and then decreases as a result of the consumption of dissolved oxygen and coke precursors. Pyrolytic deposition begins at approximately 800°F and increases monotonically.
- The transport/diffusion of reactive species to the wall (generally the location of maximum temperature and residence time) is the next most important factor affecting coke deposition for low and moderate turbulent Reynolds numbers. Increasing turbulence enhances heat transfer but also increases autoxidative coke deposition as a result of improved mass transfer. Consequently, increasing flow rate or space velocity usually increases deposit buildup in the autoxidative regime, while enlarging the flow passage (surface-to-volume ratio) reduces deposit buildup.
- Residence time is a less important factor in high-temperature heat exchangers where the coke deposition process is controlled by diffusion (i.e., low and moderate Re). However, coke deposition can be reduced by significantly increasing heat flux, while increasing flow rate at high Reynolds numbers and decreasing the residence time, the resultant higher wall temperatures notwithstanding.
- For the range of pressures examined (600 to 1200 psi), pressure is not a significant factor affecting autoxidative coke deposition.
- Techniques for providing interchannel communication and reducing the transverse temperature gradient (e.g., fins) can reduce deposit buildup. High aspect ratio streamline-shaped pin fins offer potential for lowering coke deposition, significantly enhancing heat transfer and increasing lifetime relative to continuous channels.

ACKNOWLEDGMENTS
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