NASA/TM-20260005800

Fuel Heating System Design and Thermal Modeling for Aviation Combustion Research

Zhuohui He
Glenn Research Center, Cleveland, Ohio

August 2026

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION.
  Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM.
  Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT.
  Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION.
  Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION.
  Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION.
  English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

NASA/TM-20260005800

Fuel Heating System Design and Thermal Modeling for Aviation Combustion Research

Zhuohui He
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

August 2026

Acknowledgments

This work was supported by the Subsonic Vehicle Technologies and Tools (SVTT) Project. The author gratefully acknowledges the CE-13C combustion test facility team—Pesek, Steven W., Ross, David J., Mitchell, Jonathan L., and Revilock, Alan J.—for their essential contributions in building and operating the fuel-heating system.

This report contains preliminary findings, subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by technical management.

This report is available in electronic form at https://www.sti.nasa.gov/ and https://ntrs.nasa.gov/

NASA STI Program/Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Fuel Heating System Design and Thermal Modeling for Aviation Combustion Research

Zhuohui He
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Aviation fuels offer good heat-sink capability that supports aircraft thermal-management strategies and advanced propulsion concepts. Maintaining well-controlled fuel temperatures is essential for understanding combustion behavior and conducting high-temperature fuel experiments. This report describes the modeling and experimental validation of a portable, high-temperature Jet A conditioning system developed for multiple NASA Glenn Research Center combustion facilities. The system uses a circulating-oil heater and modular tube-in-tube heat exchangers (HX) capable of heating Jet A to nearly 600 K. Experimental data from the CE-13C combustion test facility were used to determine overall heat-transfer coefficients, which increased with fuel flow rates. Using these calculated coefficients, the analysis indicates that fuel flow rates of approximately 23 kg/hr or greater are necessary to reach an outlet fuel temperature of 600 K. Thermal Desktop models were created to analyze heat exchanger configurations and predict performance across a range of operating conditions. Model predictions were generally within ±20% of the CE-13C test data but became less accurate at fuel flow rates of 3 kg/hr or lower. The models also predict that the “small” exchanger performs better than the “large” exchanger when fuel flow rates are below 100 kg/hr due to stronger fuel-side convection. These results provide guidance for sizing future fuel heating systems for combustion research applications.

Introduction

Aviation fuels possess substantial heat-sink capacity that can be utilized to absorb thermal loads from aircraft electrical or avionics systems, or to serve as the working fluid in recuperative engine-cycle concepts. Research shows Jet A fuel is a better coolant than fan air (Ref. 1). Because fuel temperature affects ignition characteristics and overall combustion behavior, the ability to deliver accurately controlled, elevated-temperature fuel is essential for future fuel–air-mixer development and evaluation. To support research requiring elevated-temperature fuel, a portable heated-fuel delivery system was designed and implemented. The system conditions Jet A fuel using a circulating-oil temperature-control unit in combination with tube-in-tube stainless-steel heat exchangers capable of achieving temperatures up to 600 K. Thermal Desktop models were developed to estimate system performance and to evaluate alternative heat exchanger configurations. The model predictions are compared against experimental data obtained in the CE-13C combustion facility in this study.

System Design and Modeling

Fuel Heating System Design and Operation

Fuel-delivery systems at the NASA Glenn Research Center typically pump Jet A from storage to pressures approaching 1000 psia. Flow distribution is provided by Badger control valves with mass-flow verification via Coriolis meters. Nitrogen purge capability is included from upstream of the badger control valves for emergency shutdown scenarios (Figure 1). Typical maximum fuel flow rates for the fuel lines are listed in Table 1 for CE-13C and CE-5 test facilities (Ref. 2).

For the fuel heating system design, each fuel line incorporates an independent heating module consisting of a circulating-oil temperature control unit and a stainless-steel tube-in-tube heat exchanger as shown in Figure 1.

The circulating oil temperature control system is a MOKON HTF 600 Series unit equipped with a positive-displacement pump capable of supplying up to 100 psid for oil recirculation. Although the oil flow rate is not directly measured during operation, Thermal Desktop modeling indicates that the oil mass flow rate typically ranges from 245 to 325 kg/hr for the "small" heat exchanger configuration and from 3750 to 3913 kg/hr for the "big" heat exchanger configuration over an oil-temperature span of 319 to 600 K. The MOKON unit is installed in the test cell adjacent to the combustion rig, while temperature control is performed remotely from the neighboring control room. The unit's integrated PID controller provides reliable temperature regulation, and transitions between oil temperature setpoints are generally achieved within 30 min for most conditions.

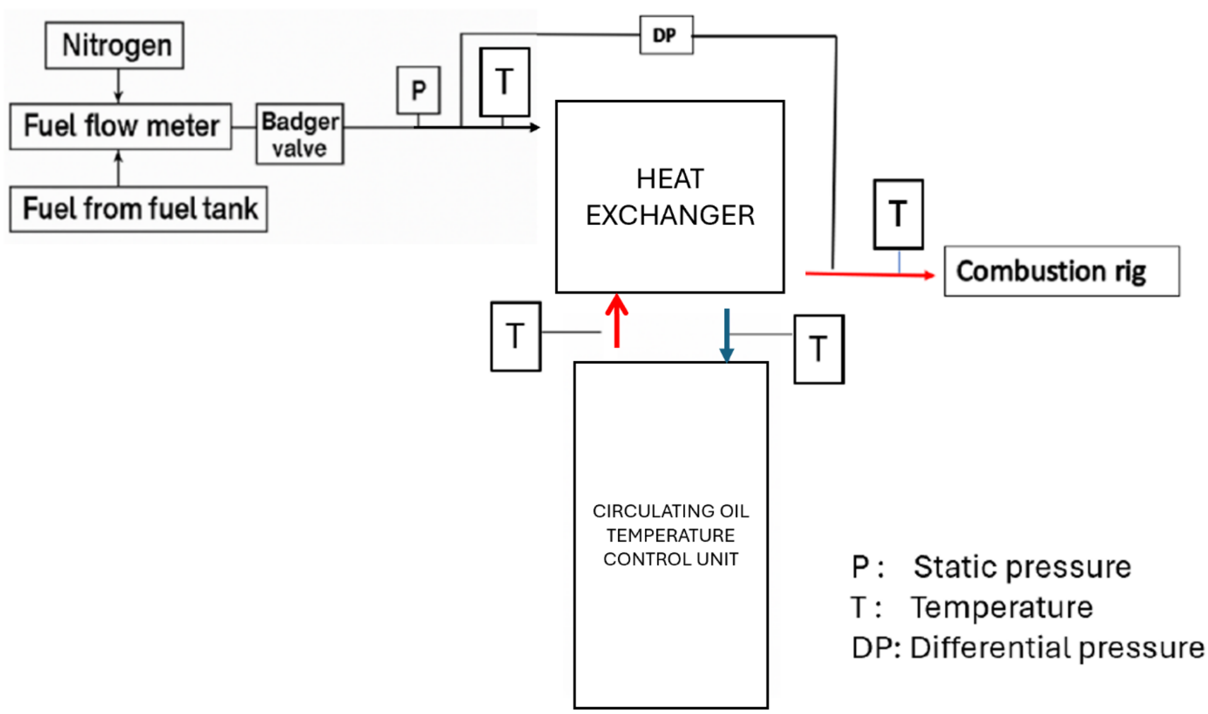

Figure 1. Fuel heating system design for single fuel line.

Table 1. Typical maximum fuel flow rates of the combustion test facilities

Test facility	Fuel line 1, kg/hr	Fuel line 2, kg/hr	Fuel line 3, kg/hr
CE-13C	6	27	—
CE-5	120	176	176

Table 2. Heat exchanger size

Heat exchanger	Inner tube outer diameter, cm	Outer tube outer diameter, cm	Heat-transfer area, m²	Tube length, m
Small	0.635	1.270	0.12	6
Big	1.27	2.54	0.24	6

The heat exchanger, manufactured by Sentry, is a tube-in-tube heat exchanger made of 316 stainless steel. Two different sizes of the heat exchanger are considered. The diameter of the tubes and heat exchange area are listed in Table 2.

Both the inner and outer tubes of the heat exchanger are rated up to 2300 psig and 810 K. The heat exchanger is placed next to the combustion rig at a level higher than the fuel injection point, allowing Jet A fuel to easily drain out of the heat exchanger in case of an emergency shutdown. The heat exchanger is counter-flowed. The heated oil enters the outer tube at the bottom end and exits at the top end, returning to the circulating oil temperature control system. The Jet A fuel (at various flow rates and pressures up to 1000 psia) enters the inner tube of the heat exchanger through the top end and exits at the bottom end before being injected into the combustion rig for combustion. Differential pressures, static pressures, and temperatures are measured before and after the heat exchanger for both the inner and outer tubes as labeled in Figure 1.

During CE-13C testing, Jet-A fuel is first delivered directly from the facility's storage tank at temperatures between 273 K and 310 K to establish a stable combustion condition before any heating is applied. Once steady operation is confirmed, the circulating oil temperature control system is started, and heated oil is directed through outer tube of the heat exchanger. The target Jet A temperature is then achieved by increasing the oil temperature. Before the combustion rig is shut down, the oil temperature control unit is cooled down to reduce the risk of coke building up within the heat exchanger.

Thermal Desktop Modeling

A simplified three-dimensional Thermal Desktop model of the heat exchanger geometry was created using SpaceClaim and meshed in Thermal Desktop. Figure 2 shows a screenshot of the Thermal Desktop model alongside a photograph of the "small" heat exchangers installed in the CE-13C test facility. Although the experimental coil and the simulated coil differ in the number of helical turns, the total tube lengths and cross-sectional geometries are matched. In the CE-13C setup, the outlet fuel temperature is measured approximately 0.8 m downstream of the heat exchanger exit, just before the flow enters the combustion rig. To replicate this measurement location in the simulation, an extended ¼-in. stainless-steel tube section (I.D. = 0.465 cm) was added to the Thermal Desktop model.

The outer surface of the outer tube is thermally coupled to a plenum node representing the test cell environment, with heat loss modeled through forced convection using an air velocity of 1 m/s under ambient temperature and pressure conditions. The surface of the extended tube is wrapped with insulated fiberglass in the CE-13C setup. For this section, natural convection is applied to the outer surface of the extended tube in the Thermal Desktop model to represent the worst-case heat loss scenario.

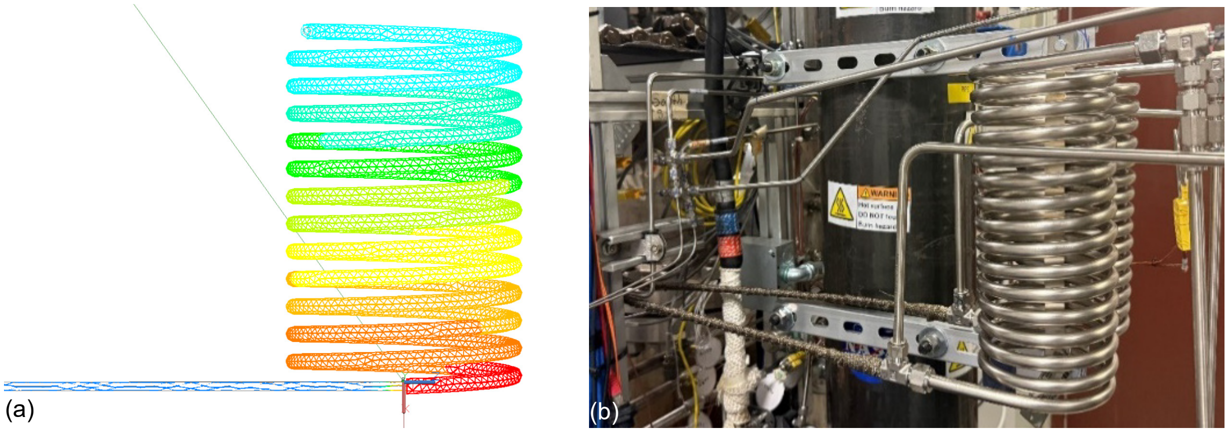

Figure 2. (a) Thermal Desktop model; total tube lengths and cross-sectional flow geometries are matched. (b) Heat exchanger setup in CE-13C.

Table 3. Pressures and temperatures of the fluid pipes

	Oil	Jet fuel
Inlet plenum	P = 104 psia, $T = T_{oil,in}$	P = adjusted to match fuel flow rate, $T = T_{fuel,in}$
Outlet plenum	P = 14 psia, $T = T_{oil,in} - 15$ K	P = 200 psia, T = 500 K

Two separate fluid-pipe models are implemented to simulate flow through the inner and outer tubes. The inner tube surface defines the outer boundary of the Jet A flow pipe, while the inner surface of the outer tube and the outer surface of the inner tube together define the boundaries of the oil flow pipe. Thermophysical properties for Jet A and the heating oil are represented using C12 (dodecane) and C22 (docosane) from the Thermal Desktop fluid databank.

The inlet and outlet of each fluid pipe are connected to plenum lumps, whose inlet temperatures and pressures are set according to the conditions described in Table 3. The oil outlet plenum pressure is set to 14 psia, and the pressure drop for the oil pipe is fixed at 90 psid. For the Jet-A pipe, the outlet plenum pressure is set at 200 psia, and the inlet plenum pressure is adjusted until the simulated flow rate matches the target value. The experimental outlet fuel pressure varies and depends on the combustion-rig pressure and the required pressure drop across the fuel injector. For this test in CE-13C, the fuel pressure at the heat exchanger outlet ranged between 145 and 650 psia. The inlet temperatures for the oil and Jet-A plenums are set either to the experimental values (Table A.1) or to the desired operating conditions.

With this setup, both the oil and Jet A streams remain fully in the liquid phase throughout their respective pipes, and the heat transfer calculations show no sensitivity to the fluid pressures. In addition, the outlet plenum pressures and temperatures do not influence the final lump pressures and temperatures for either pipe. These final lump temperatures and pressures are treated in the model as the outlet temperatures and pressures for the oil and fuel streams.

Results and Discussion

Experimental Results and Data Analysis

Experimental testing in the CE-13C facility employed Jet A (A2) fuel with flow rates ranging from 2 to 18 kg/hr, constrained by the operating limits of the installed fuel-injector hardware. The facility uses two independent fuel lines, each equipped with a "small" stainless-steel tube-in-tube heat exchanger for fuel conditioning. During testing, inlet and outlet temperatures of both the oil and fuel streams, the corresponding fuel mass flow rates, and the Reynolds numbers were recorded and are summarized in Appendix A, Table A.1.

To determine how hot the Jet A fuel can get with this fuel heating system, the overall heat-transfer coefficient (U) is first calculated using the Log Mean Temperature Difference (LMTD) method (Ref. 3), assuming the heat gained by the Jet A fuel ($\dot{Q}_{fuel}$) is equal to the heat transferred through the heat exchanger.

$$U = \frac{\dot{Q}_{fuel}}{A\,\Delta T} = \frac{\dot{m}_{fuel} Cp_{fuel}(T_{f,out} - T_{f,in})}{A\,\Delta T}$$

Experimental results show that U increases with Jet A flow velocity, as demonstrated in Figure 3. The corresponding fuel Reynolds numbers range from 205 to 7150. A correlating equation was developed to relate U to Jet A velocity (v), expressed as:

$$U = 864.73\, v^{1.4} = 864.73 \left(\frac{\dot{m}_{fuel}}{\rho_{fuel} A_{flow}}\right)^{1.4}$$

Assuming the oil temperature control unit is operated at its maximum setting ($T_{oil,in}$ =616 K, $T_{oil,out}$ = 606 K) and T_{fuel} in =300 K, the maximum outlet fuel temperatures at various mass flow rates can be estimated with the following equation:

$$\dot{m}_{fuel} = \frac{UA\,\Delta T}{Cp_{fuel}(T_{f,out} - T_{f,in})}$$

where, A_{flow}= pipe cross-sectional area (0.173 cm^2 for the "small HT"), A =heat-transfer surface area, $\Delta T = \frac{\Delta T_{oil} - \Delta T_{fuel}}{\ln\left(\frac{T_{oil,in} - T_{fuel,out}}{T_{oil,out} - T_{fuel,in}}\right)}$, and Jet fuel properties are listed in Table A.2 in Appendix A.

As shown in Figure 4, reducing the Jet A mass flow rate lowers the convective heat-transfer rate on the fuel side, which in turn requires a larger temperature difference between the oil and fuel to achieve the target outlet fuel temperature. To reach 600 K, the fuel mass flow rate needs to be approximately 23 kg/hr or higher.

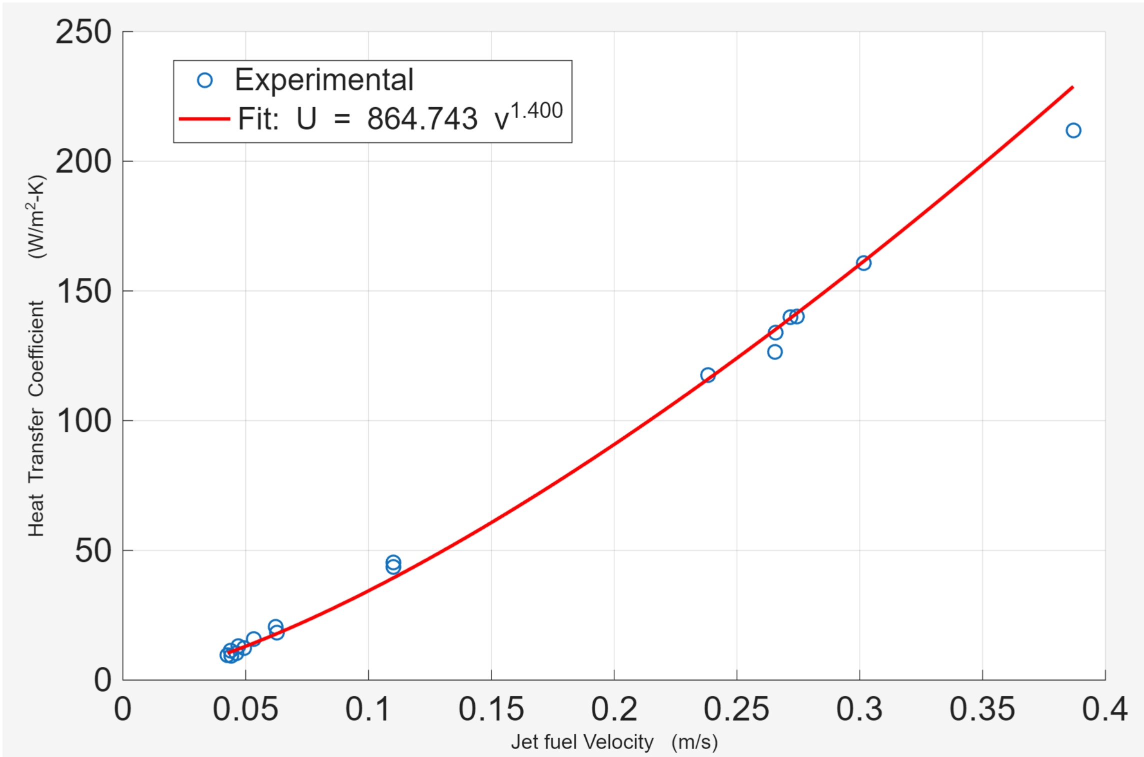

Figure 3. Calculated overall heat-transfer coefficient as a function of Jet A fuel flow velocity.

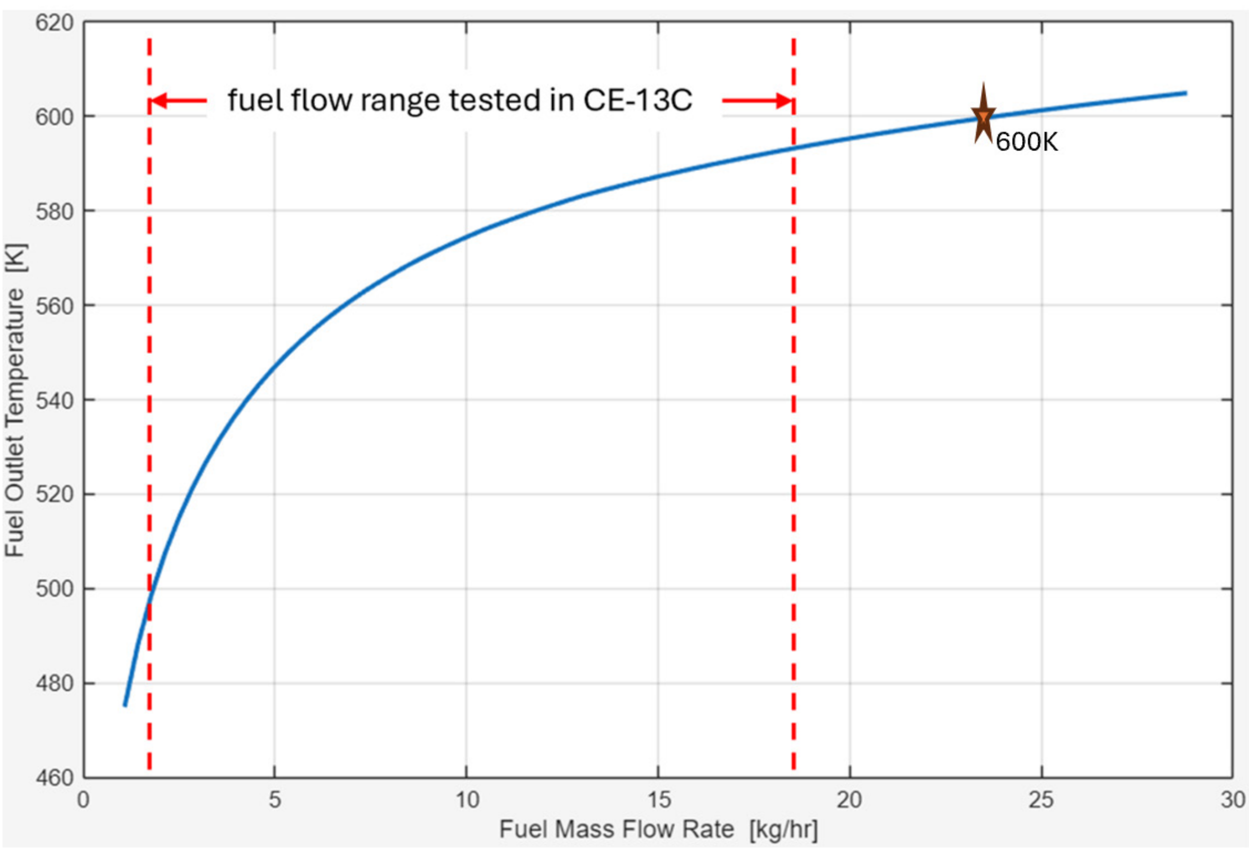

Figure 4. Calculated maximum fuel outlet temperature as a function of Jet A fuel flow rates.

Thermal Desktop Modeling Results

Multiple operating conditions listed in Table A.1 were simulated in Thermal Desktop to evaluate how accurately the model predicts fuel temperature rise. For these simulations, the oil inlet temperature, fuel inlet temperature, and fuel flow rate were matched to the corresponding experimental values. Figure 5 presents the predicted oil and fuel temperature profiles along the heat exchanger tubes and the extended tube section, together with the experimental data from Point 11 in Table A.1. The predicted oil outlet temperature agrees closely with the measurement, while the predicted fuel outlet temperature is underestimated by approximately 22 K. The model also indicates that heat loss from the extension tube to the environment is minimal; the temperature drop between 6 and 6.8 m is less than 1 K.

Figure 6 shows that the Thermal Desktop model overpredicts fuel temperature rise at low fuel flow rates and underpredicts it as fuel flow rates increase. While most cases exhibit about 20% deviation from measurements, errors increase to 27–63% when the fuel flow rate drops to about 3 kg/hr or below. These results suggest that the heat-transfer properties assigned to C12 (dodecane) in Thermal Desktop may not adequately represent Jet A. Specifically, the model appears to assume a higher-than-actual heat-transfer rate at low fuel flow rates and a lower-than-actual heat-transfer rate at higher fuel flow rates. For example, the experimental overall heat-transfer coefficient is about 10.4 W/(m²·K) versus 53.1 W/(m²·K) predicted at a fuel flow rate of 2.14 kg/hr (Point 12), whereas at 12.60 kg/hr (Point 13), the experimental value is about 138.4 W/(m²·K) compared to 106.0 W/(m²·K) predicted.

Fuel-heating capabilities for both the “small” and “big” heat exchangers were evaluated with Thermal Desktop models over a wider range of fuel-flow conditions than can be achieved in the CE 13C combustion test facility. The results in Figure 7 show that the “small” exchanger yields higher predicted outlet fuel temperatures for fuel-flow rates below approximately 100 kg/hr. Its smaller inner-tube diameter increases the Jet A flow velocity and therefore the convective heat-transfer rate. However, the reduced outer-tube size limits the oil’s heat-carrying capacity for the “small” exchanger. In contrast, the “big” heat exchanger accommodates a larger oil-flow capacity and thus provides higher outlet fuel temperatures once the fuel-flow rate exceeds 100 kg/hr.

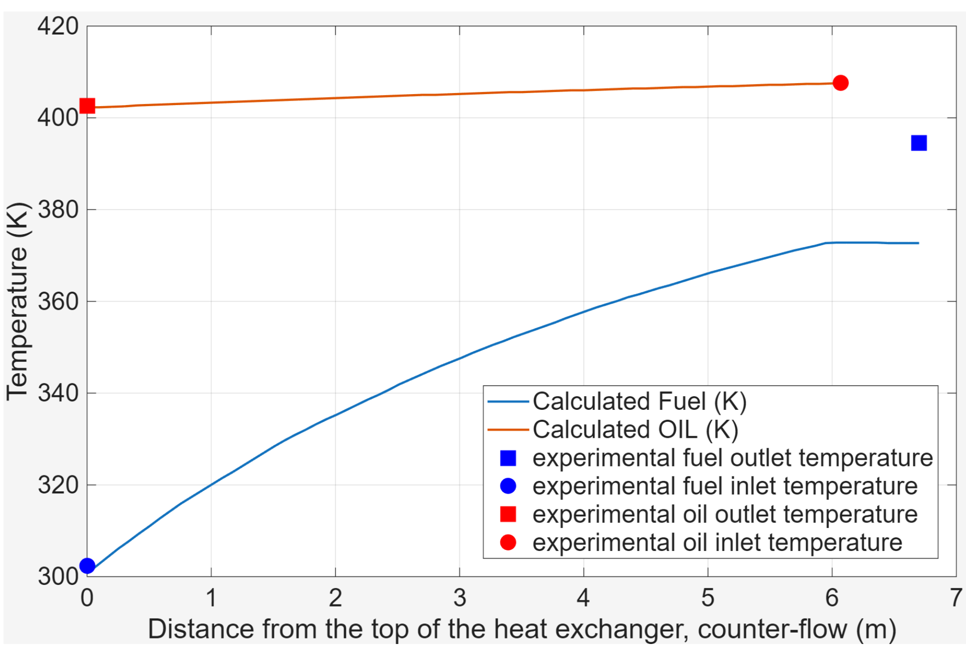

Figure 5. Calculated temperature profiles of the heated oil and fuel in the heat exchanger versus the experimental inlet and outlet temperatures (Point 11 of Table A.1).

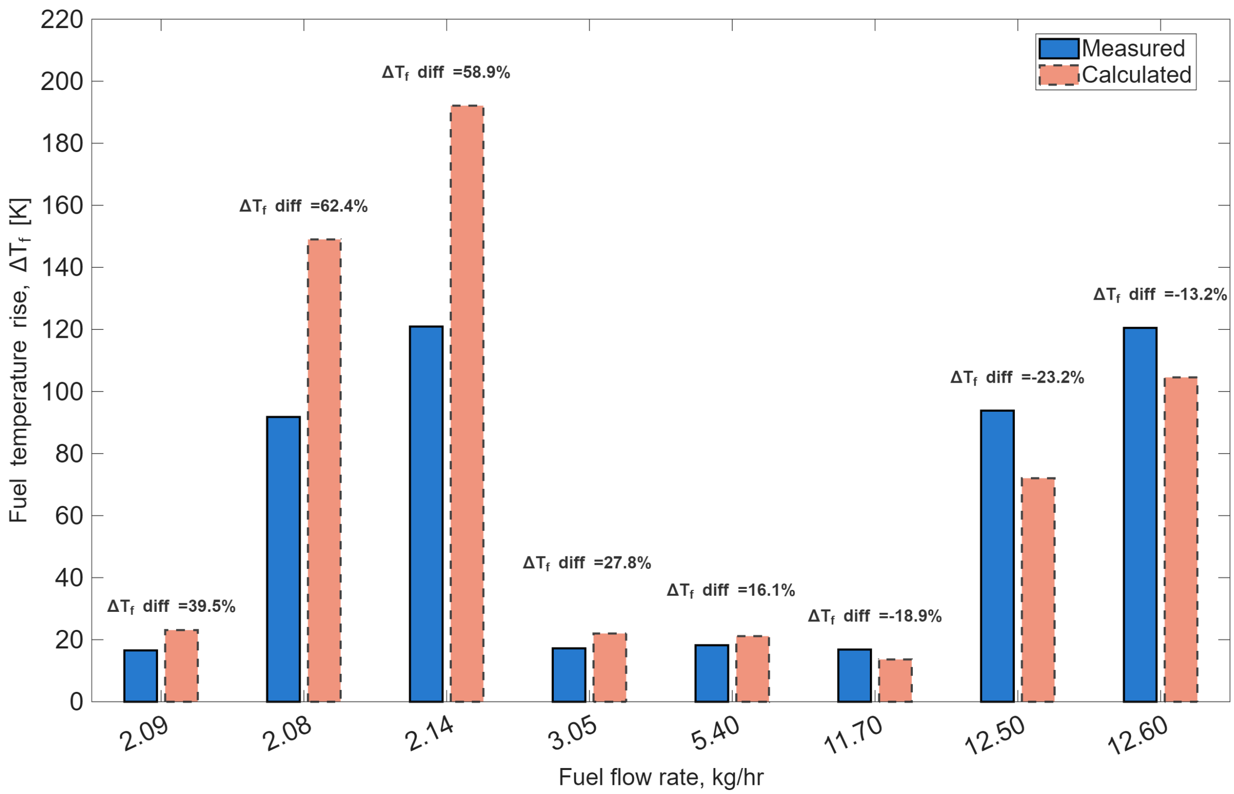

Figure 6. Comparison of fuel temperature rise between experiment and calculation.

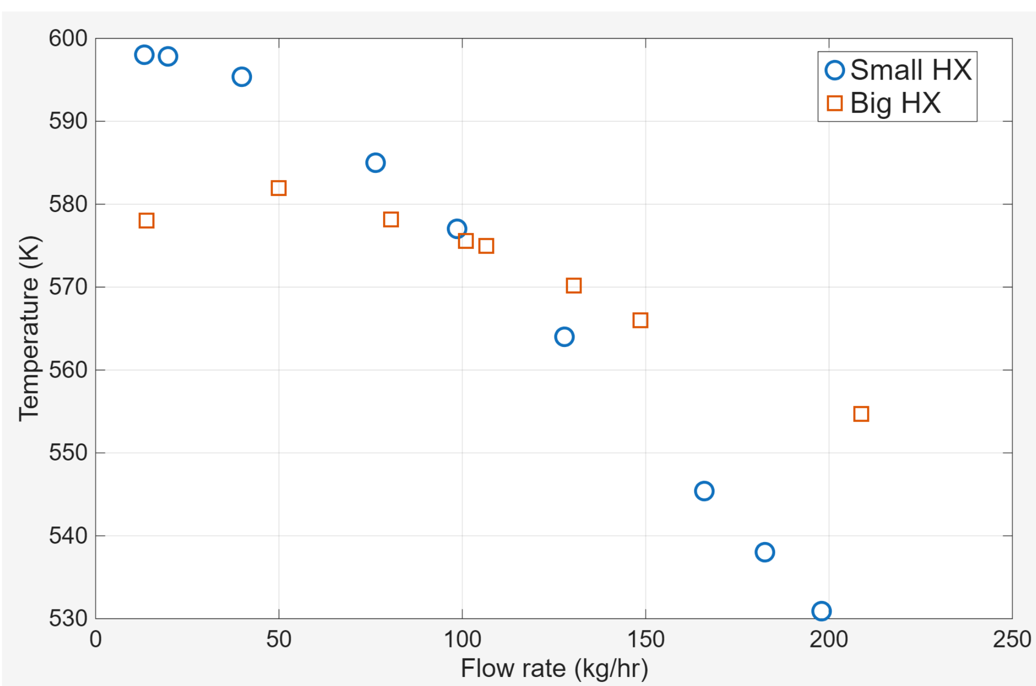

Figure 7. Fuel outlet temperature as a function of fuel flow rate with oil inlet temperature set at 600 K for both "small" and "big" heat exchangers (Thermal Desktop results).

Conclusions

A fuel heating system capable of conditioning Jet A to temperatures approaching 600 K was successfully developed and demonstrated in the CE-13C combustion test facility. Experimental measurements and analysis confirmed that a single "small" tube-in-tube heat exchanger cannot achieve 600 K fuel temperatures at flow rates below approximately 23 kg/hr due to low heat-transfer rates. Although the Thermal Desktop calculations do not match the experimental fuel-temperature rise well, they provided an order-of-magnitude estimate that was useful for sizing the heat exchangers. Modeling results also show that the "small" exchanger provides superior performance up to roughly 100 kg/hr because of its higher fuel-side convective heat-transfer rate, whereas the "large" exchanger becomes advantageous at flow rates above 100 kg/hr when oil-side thermal capacity becomes a limiting factor for the "small" heat exchanger. These results provide a validated framework for sizing heated-fuel systems and support future combustion research applications requiring stable, well-controlled, high-temperature fuel delivery.

Appendix A.—Experimental Data and Jet Fuel Properties

Table A.1. Fuel mass flow rate and experimental inlet and outlet temperatures for oil and fuel

Point	Oil inlet, K	Oil outlet, K	Fuel inlet, K	Fuel outlet, K	Fuel flow rate, kg/hr	Reynolds number jet fuel
1	319	317	297	315	5.40	547
2	320	318	297	316	5.40	549
3	317	314	297	314	11.70	1163
4	317	313	297	314	13.00	1280
5	320	319	298	315	3.05	309
6	322	320	298	312	2.09	205
7	322	320	298	314	2.15	215
8	322	320	298	314	2.31	232
9	322	320	298	315	2.61	265
10	456	453	302	394	2.08	539
11	408	403	301	395	12.50	3197
12	502	497	303	424	2.14	737
13	439	433	302	422	12.70	4252
14	504	500	303	425	2.14	746
15	438	432	301	422	12.60	4203
16	569	563	307	475	2.22	1214
17	497	488	303	474	13.60	7150
18	490	484	308	436	2.88	1156
19	452	444	306	436	17.80	7008

Table A.2. Jet fuel properties

Properties	Values	Test method
Heat capacity, Cp, J/kg-K	$3.8T(K) + 814.53$	E1269 (273 to 373 K)
Thermal conductivity, k, W/m-K	$0.176 - 2.0 \times 10^{-4}T(K)$	ASTM D7896 (273 to 323 K)
Density at 290 psia, ρ, kg/m^3	$1021.61 - 0.7710T(K)$	Reference 4 (270 to 470 K)

References

1. Bruening, G. B., and Chang, W. S., “Cooled Cooling Air Systems for Turbine Thermal Management,” ASME Turbo Expo 1999: International Gas Turbine and Aeroengine Congress & Exhibition, Paper No. 99-GT-014, 1999.
2. “Combustor Facilities.” *NASA Glenn Research Center*, 3 Feb. 2025, https://www.nasa.gov/centers-and-facilities/glenn/combustor-facilities/. Accessed 8 June 2026.
3. Qiao, H., 2018, “Correction of Log Mean Temperature Difference Method and Effectiveness-NTU Relations for Two-phase Heat Transfer with Pressure Drop and Temperature Glide,” *International Refrigeration and Air Conditioning Conference at Purdue*, Paper No. 1923.
4. Outcalt, S. L., Laesecke, A., Freund, M. B., Bruno, T. J., Huber, M. L., Lemmon, E. W., McLinden, M. O., Perkins, R. A., Smith, B. L., and Widegren, J. A., “Thermodynamic, Transport, and Chemical Properties of ‘Reference’ JP-8,” NISTIR 6659, National Institute of Standards and Technology, Boulder, CO, July 2010.