

Characterizing Heat Flux in the miniature Arc jet Research Chamber (mARC II)

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The second-generation miniature Arc jet Research Chamber (mARC II) at NASA Ames Research Center produces small-scale high enthalpy flows relevant for entry systems ground testing. This facility is aimed at applications such as new arc jet flow diagnostics and new arc column diagnostics. The mARC system has previously been shown capable of delivering heat fluxes between 800 and 1900 W/cm². New work shows that the facility is also capable of delivering heat fluxes as low as 200 W/cm².

Nomenclature

<i>ARC</i>	=	Ames Research Center
<i>DAQ</i>	=	Data acquisition system
<i>EMI</i>	=	Electromagnetic interference
<i>mARC II</i>	=	miniature Arc jet Research Chamber (second-generation)
<i>NASA</i>	=	National Aeronautics and Space Administration
$\dot{q}$	=	Heat flux
<i>P</i>	=	Pressure
<i>T</i>	=	Temperature
<i>t</i>	=	Time
<i>I</i>	=	Arc current
<i>z</i>	=	Axial distance from the nozzle exit to the sensor insertion location

I. Introduction

The NASA Ames Thermophysics Facilities Branch operates six high-power (10 – 60 MW) arc heaters in four different arc jet test bays for entry systems testing [1]. Operational complexity inherently accompanies these high-power facilities. Certain test programs are better suited to smaller scales. The mARC II facility serves as a test bed for exploring new diagnostics, sensors, and even materials at conditions relevant to the high-power arc jets, but on a much smaller scale and at a lower operating cost, requiring fewer operations personnel and less facility

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maintenance. Figure 1 shows the mARC II jet as it exits the nozzle and expands into the vacuum chamber. The history and operating envelope of the mARC II facility has been described previously [2-4]. Recently, customer requests for even lower heat flux values than were previously achieved have pushed the team to mARC II configurations that provide heat fluxes as low as 200 W/cm². The expansion of the mARC II heat flux envelope is quantified here. In addition, the facility is constantly undergoing improvements. Descriptions of the recent mARC II upgrades are also included.

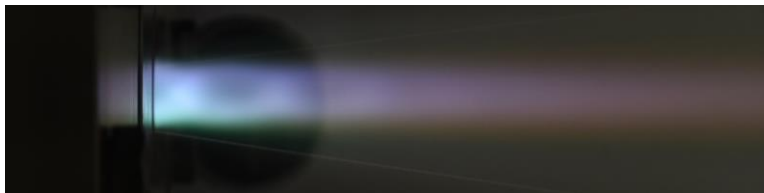


Figure 1: Photo of the mARC II jet. Test mARC001 Run 20: 100A, 0.25 g/s air (1/20 sec, f/6.3, 25 mm, ISO 200 with UV filter).

II. Experimental Setup

A. Arc Heater

The mARC II is a 30-kW segmented constricted arc heater with the capability of reaching flow bulk enthalpies of 4-12 MJ/kg (sonic flow) in air. The facility can run air or CO₂/N₂ gas mixtures. The current work is carried out in air. The exit Mach number ranges from approximately 1.5 to 5, depending on the injected mass flow rate and the set current. A Hypertherm MAX200 plasma cutter serves as the power supply and gas control system for mARC II. The Hypertherm torch body (containing the cathode) is mounted into the in-house designed constricted heater. Tie rods maintain compression on the two constrictor disks (one with a pressure tap), the anode, and a converging-diverging nozzle. Each component is insulated from the adjacent component by a boron nitride disk. The nozzle throat diameter is 5.56 mm and the nozzle exit diameter is 18.7 mm. The layout of the heater is shown in Fig. 2.

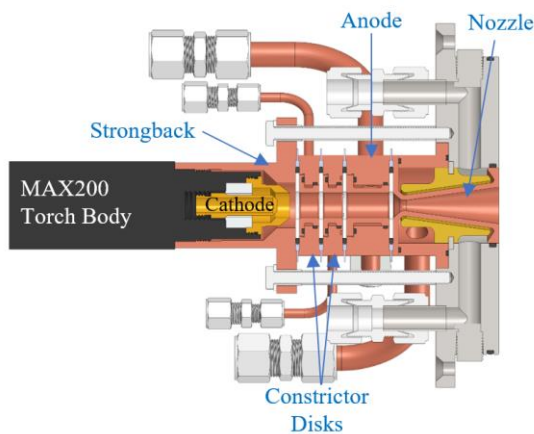


Figure 2: mARC II Arc Heater.

B. Instrumentation

Facility data are acquired for the standard system parameters, including arc current, arc voltage, supply gas mass flow rates, column pressure, and chamber pressure. A heat flux sensor and a pitot probe are also available for flow characterization. The locations of these measurements are shown in Fig. 3.

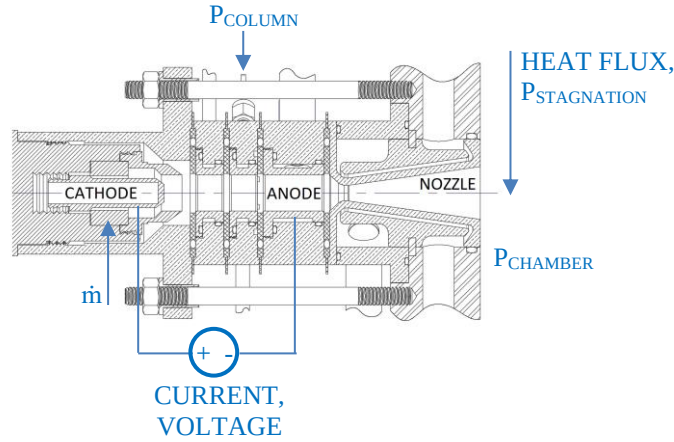


Figure 3: Schematic of Measurements Taken During mARC II Operation.

Table 1: List of Measurements Taken During mARC II Operation

Measurement	Description	Units	Instrument
U	Arc voltage	V	Ohio Semitronics VT7-007E-11-TP
I	Arc current	A	Ohio Semitronics CTL-401S/300 and CTA 201H
$\dot{m}$	Supply gas mass flow rate	g/s	Sage SIP-030-DC24-AIR
P_{column}	Column pressure	Pa	Setra Model 730 SN 6976651
P_{chamber}	Vacuum chamber pressure	Pa	Inficon CDG025D, 0-10 Torr + 0-1000 Torr
$P_{\text{stagnation}}$	Stagnation pressure	Pa	Medtherm pitot probe Model 12-PP-1.0-6-10-50553 Endevco piezoresistive transducer Model 8530C-15
$\dot{q}$	Heat flux in plasma jet	W/cm ²	Medtherm water-cooled Gardon gauge Model 12-3000-1.0-6-72-21631T

A Gardon heat flux gauge measures the flow condition downstream of the nozzle exit (location marked as Heat Flux in Fig. 3). This Gardon gauge is mounted in a water-cooled 4.75 mm (0.187 in, as specified on the drawing) diameter hemispherical copper body (Fig. 4a) and came from the manufacturer with an embedded thermocouple for monitoring gauge temperature. A matching pitot probe in a water-cooled 4.75 mm diameter hemispherical copper body provides a corresponding measurement of stagnation pressure at each condition (Fig. 4b). These are the same sensors that were used for heat flux and stagnation pressure measurements in mARC 1 [3]. During the present work, the heat flux and stagnation pressure sensors were inserted into the flow at the same condition on separate runs. However, mARC II is now set up to accommodate two water-cooled sensors on the trident. This enables a nearly simultaneous measurement of heat flux and stagnation pressure that will be standard practice for future tests.



Figure 4: a) Water-cooled Gardon heat flux gauge (center), and b) Water-cooled pitot probe.

Two monochrome Chronos 1.4 high-speed cameras are now installed on the mARC II chamber for observation of the jet itself. The standard infrared cut-off filter has been removed from both cameras to enable observations into the near infrared. Both cameras utilize a Navitar Zoom 7000 macro lens (close-up lens removed) for imaging the arc jet exit

plane. The cameras are mounted perpendicular to the flow axis at the overhead window of the mARC II chamber and are focused on the centerline of the nozzle plane. These cameras have undergone initial systems testing and future work includes observation of the flow to determine symmetry and shock structure.

C. Infrastructure Improvements

The main support systems for mARC II have been described previously [4], but the system has been continuously improved over the last few years. The latest overview photo of the mARC II system is shown in Fig. 5.

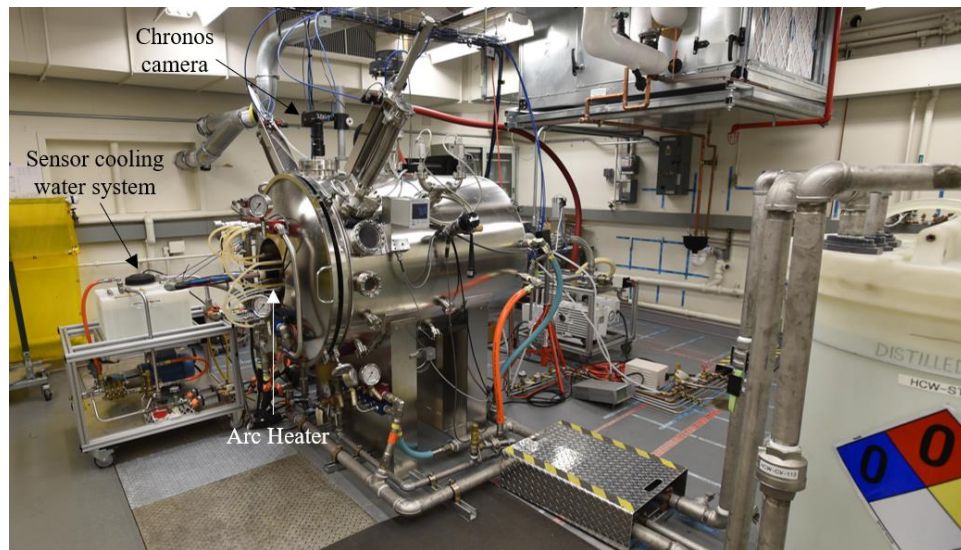


Figure 5: Overview of the mARC II system.

The recent addition of a trident sweep arm (Fig. 6 and Fig. 4a) and its corresponding sweep motor (Fig. 7) have enabled automated sensor sweeps and dwells in the flow. The trident arm was designed and fabricated in-house and was installed on the sweep motor in preparation for the heat flux measurements reported here. The trident assembly has 65 mm of axial travel, which provides the flexibility to place the sensors in the flow at the desired axial distance from the nozzle exit. This trident exposes the sensors to the flow within fractions of a second of each other, enabling direct comparison between sensors. It was designed for short sensor insertions and is not water-cooled.

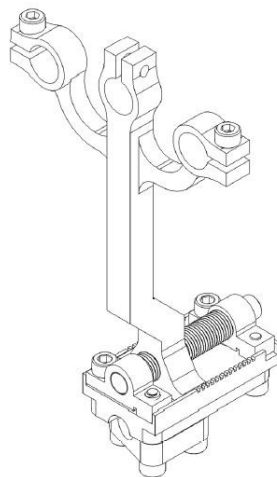


Figure 6: Trident Sweep Arm.

The new sweep arm motor (Clearpath CPM-SCSK-2311S-ELSA) not only offers the torque and velocity performance necessary for mARC II testing but also a suite of software control features within an all-in-one servo motor system. The system uses distributed and scalable architecture to allow for easy scaling and multi-axis motor applications (up

to 16 motors on a single communication port). The motor offers unique motion profiles such as asymmetric moves, jerk-limited motion, and state-of-the-art anti-vibration features for highly accurate motion applications. Furthermore, it offers robust communication for high-speed commands (over 1,000 commands per second) and noise immunity through optically isolated inputs and noise-resistant circuitry. The advanced system can also be implemented for high-speed automation as it allows trigger-based moves and can output parameters such as position, velocity, and torque in real-time. Lastly, the motor system integrates safety features crucial for testing such as global torque limiting and event-driven group shutdowns.

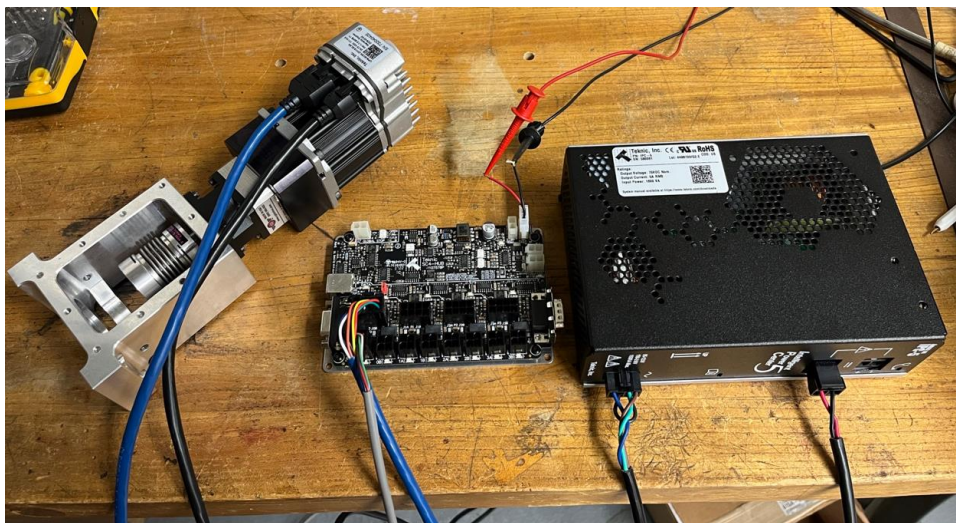


Figure 7: Sweep motor system, from left to right: servo motor, hub for multi-motor control, power supply.

The existing data acquisition (DAQ) systems' limited acquisition rate, fidelity, and expensive electromagnetic interference (EMI) isolation procedures motivated the acquisition of a secondary data acquisition system specifically for insertion arm diagnostics. This new data acquisition hardware (LabJack T7-Pro, CB37, LJTick-InAmp) has enabled fast (up to 8 kHz) high-fidelity (16-24 bit) acquisition of data from the heat flux gauge and pitot probe sensors. It can acquire simultaneous data from three sensors mounted on the sweeping trident, plus multiple sensor-health thermocouple signals (14 differential channels and 23 digital channels). The new DAQ hardware is powered by a battery and communicates via an optical ethernet link eliminating the need for channel-by-channel electrical isolation for EMI noise reduction. All input signals from the insertion arm are preconditioned by instrumentation amplifiers (LJTick-InAmp) which provide up to 200x amplification at 2 GigaOhm impedance.

In addition to these hardware improvements, mARC II operations and data management have benefited from implementation of the Big-data Efficient and Automated Science Transfer (BEAST) architecture. A detailed description of the architecture is provided in Ref. 5. In short, standardization and automation of data storage has enabled improved comparison across test campaigns, and easy access to stored data has aided in interpretation of results.

III. Operational Procedure

Prior to each run, the vacuum chamber is pumped down to approximately 15 Pa and the mass flow rate and arc current values are set to the desired values at the MAX200 control panel. When the start button is pressed, the MAX200 goes through its internal startup sequence to begin the flow of gas and start the arc. This takes less than one second. After startup, it takes approximately 20 s for the mass flow rate to settle to its set point (0.25 g/s of air in the present work). mARC II is still awaiting upgrades to its vacuum system. These upgrades are expected to occur in 2023, but until they do, the back pressure in the vacuum chamber rises continuously during all runs. It does eventually plateau, but to achieve the lowest heat flux possible with the existing vacuum system, the sensors are inserted into the jet as soon as the mass flow rate settles and before the jet collapses any further towards overexpanded. The data presented in the results section include a chamber pressure trace that shows this continual increase in back pressure throughout the run. Extracting chamber pressures at each insertion time shows that the chamber pressure varies slightly from run to run (~ 45 Pa, Table 2) just due to this variation in when the sensor was inserted into the flow. This variation in chamber

pressure is not ideal, but until the vacuum system upgrade is completed, the chamber pressure will be quantified and reported as a function of time. Two sensor dwells (each 1 s in duration) are made during each run, one as the trident sweeps forward, and another as the trident sweeps back through the flow. The trident pauses for 10 s before the return sweep, so these insertions are separated by slightly more than 10 s.

IV. Results

Given the goal of testing at lower heat fluxes than those explored in the mARC 1 characterization, the mARC II team examined the flow structure of the jet exiting the nozzle. The existing power supply cannot maintain an arc below approximately 40 A. Published mARC 1 data show that even at this lowest-power setting, measured heat fluxes were around 800 W/cm² [3]. However, these mARC 1 heat flux measurements were all made at an axial distance of 2 mm from the nozzle exit ($z = 2$ mm). Since decreasing the arc power to achieve a lower heat flux is not feasible, the present work explores alternative test locations ($z = 52$ and 68 mm) to achieve the desired heat flux.

Table 2: Average test conditions at time of 1st sensor insertion.

Condition	# Runs @ Condition	I [A]		$\dot{m}_{\text{air}}$ [g/s]		P_{chamber}^a [kPa]	P_{column} [kPa]
		Set point	Measured	Set point	Measured		
1	4	40	38.6	0.250	0.257	0.409	16.6
2	2	80	74.8	0.250	0.254	0.415	18.3
3	2	110	101.2	0.250	0.255	0.420	19.3
4	5	150	133.3	0.250	0.255	0.453	20.7

a. Insertions for each run took place at different times from the start of the experiment, so the chamber pressure at insertion varied slightly between runs.

The difference between the set and measured currents in Table 2 is observed across all of the mARC II test conditions that have been run to date — specifically, $I_{\text{measured}} = 0.923I_{\text{set}}$ (Fig. 8). Since the current sensor is measuring the current running only through the anode ground cable, but the nozzle and chamber are also grounded through a separate grounding cable, the leading hypothesis for this difference is that some current may be running to ground through this second cable. Plans for adding a current sensor to this second grounding cable should confirm or disprove this theory.

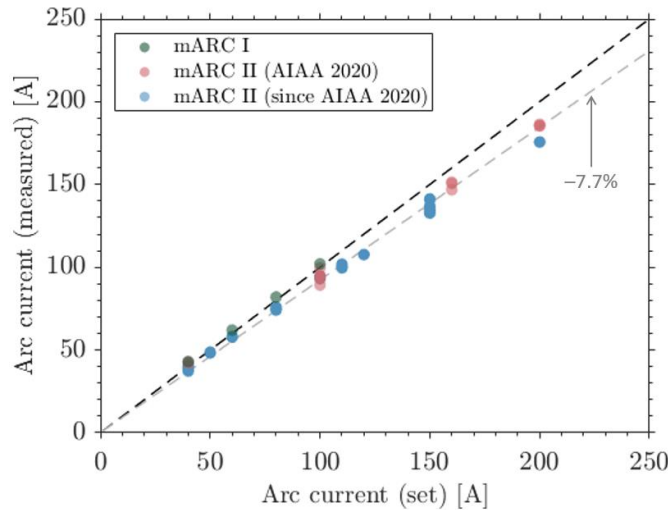


Figure 8: Deviation of measured current from set current.

Figures 9 - 13 show measured facility data and sensor data for five different measured heat fluxes. Each of the four conditions in Table 2 was run with the sensor insertion set to an axial distance of 68 mm from the nozzle exit, plus a fifth heat flux was measured at condition 4 with the sensor insertion set to an axial distance of 52 mm from the nozzle exit. The Gardon gauge and the pitot probe were each swept (at 9.5 cm/s) through the jet from West to East with a 1

s dwell on centerline. After a 10 s pause on the East side of the jet, they were swept back from East to West with another 1 s dwell on centerline. For the Gardon gauge, this was enough time to allow the measured signal from the gauge to plateau while maintaining a sensor body temperature below 232°C (505 K) to remain within the linear response region of the gauge [6]. As can be seen in Figs. 9b-13b, the thermocouple monitoring the Gardon gauge body temperature never exceeded 30 K above room temperature (323 K). For the pitot probe, 1 s was enough time to allow the gas between the probe tip and the pressure transducer to reach a steady pressure.

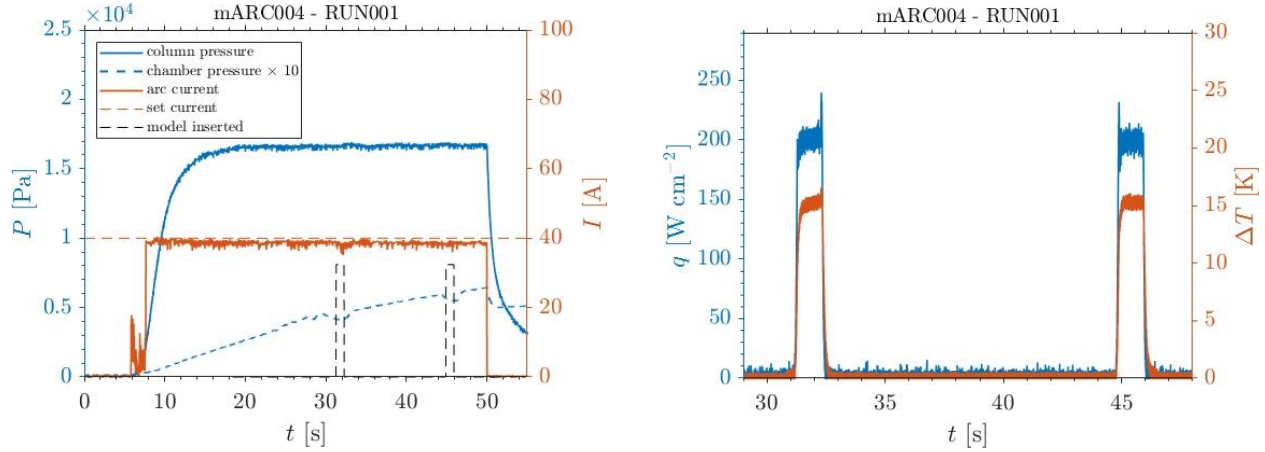


Figure 9: Cond. 1 - 40 A and 0.25 g/s air, a) Facility data, b) Gardon heat flux and sensor temperature, $z = 68$ mm.

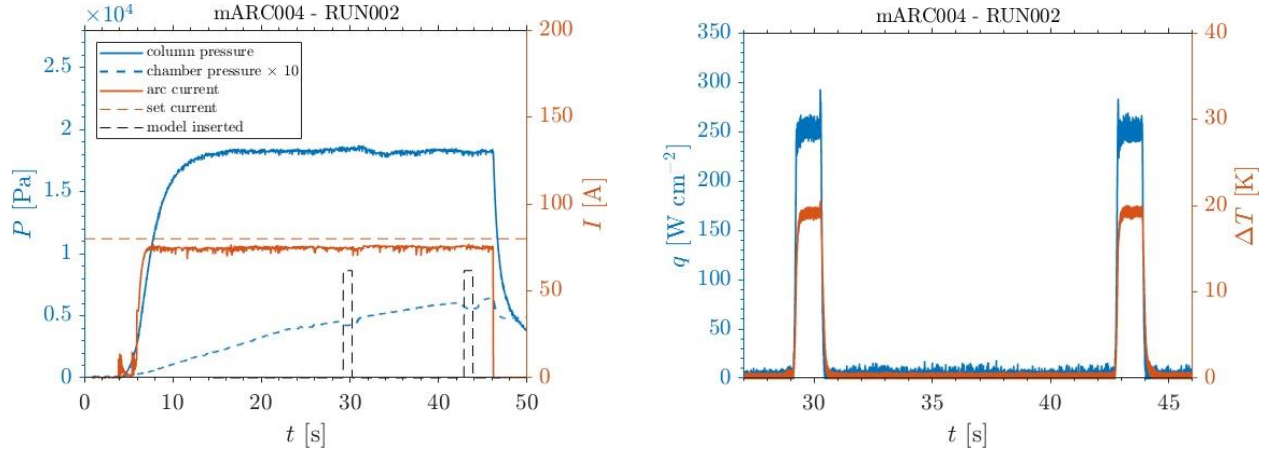


Figure 10: Cond. 2 - 80 A and 0.25 g/s air, a) Facility data, b) Gardon heat flux and sensor temperature, $z = 68$ mm.

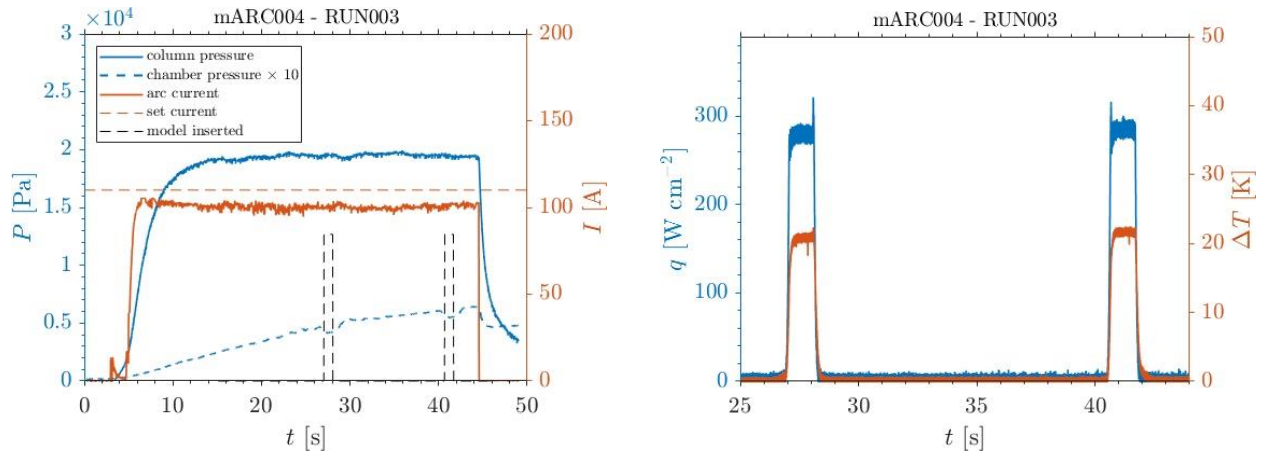


Figure 11: Cond. 3 - 110 A and 0.25 g/s air, a) Facility data, b) Gardon heat flux and sensor temperature, $z = 68$ mm.

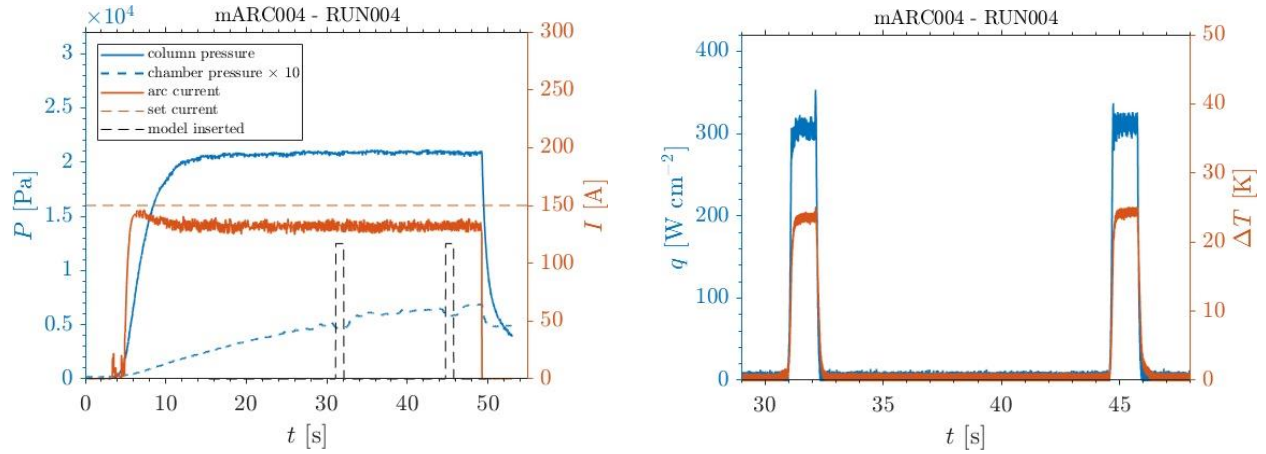


Figure 12: Cond. 4 - 150 A and 0.25 g/s air, a) Facility data, b) Gardon heat flux and sensor temperature, $z = 68$ mm.

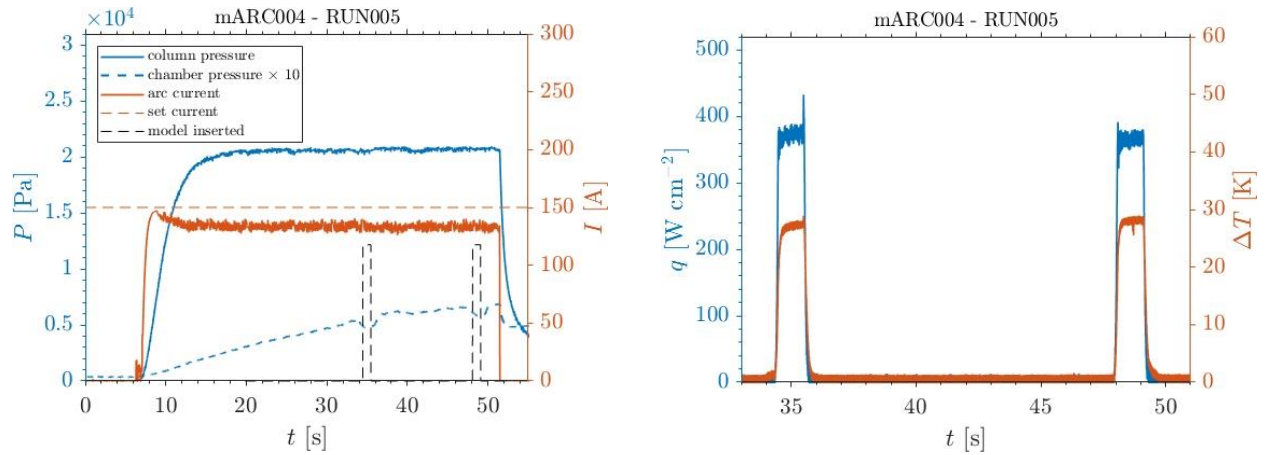


Figure 13: Cond. 4 - 150 A and 0.25 g/s air, a) Facility data, b) Gardon heat flux and sensor temperature, $z = 52$ mm.

Average values for heat flux and pressure are extracted from each insertion. Since the sensors both take approximately 0.5 s to rise to their plateau values, the average values listed in Table 3 are extracted from data acquired during the second 0.5 s that the sensors dwelled in the flow.

Table 3: Heat flux and stagnation pressure measured along centerline of mARC II.

Condition	z [mm]	Heat flux $\dot{q}$ [W/cm ²]		Temperature change ΔT [K]		$P_{\text{stagnation}}$ [kPa]	
		Insertion 1	Insertion 2	Insertion 1	Insertion 2	Insertion 1	Insertion 2
1	68	202	200	15	15	1.9	2.0
2	68	253	251	19	19	1.8	2.0
3	68	280	285	21	22	1.8	1.9
4	68	305	311	24	24	1.8	2.0
4	52	375	367	27	28	2.0	2.1

The measured heat flux at each of these conditions is plotted alongside the operational envelope reported for mARC 1 (Fig. 14). These new data significantly expand the mARC operational envelope to lower heat fluxes and stagnation pressures and satisfy the goals of the current work. In addition, mARC 1 data was only published up to 100 A while mARC II is capable of running up to 200 A. Thus, mARC II also enables future work at heat fluxes above 1900 W/cm².

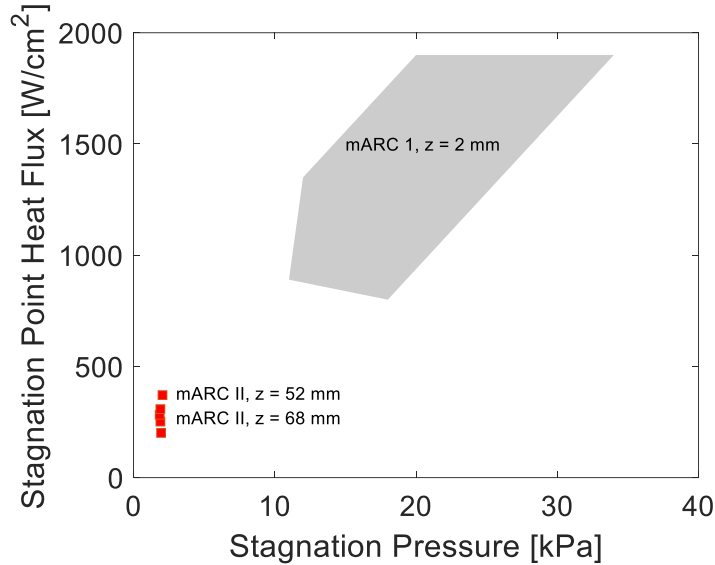


Figure 14: Expansion of operating envelope with mARC II, data from the first-generation mARC taken from Ref. 3.

V. Conclusion

Gardon gauge heat flux measurements at mARC II have shown that at axial distances of 52 mm and 68 mm from the nozzle exit, the facility can provide flow conditions corresponding to cold-wall heat flux measurements as low as 200 W/cm². This is a significant expansion of the mARC operational envelope to heat fluxes much lower than those published for mARC 1. Future work will include a comparison of this Gardon gauge data with heat flux derived from coaxial thermocouple heat flux measurements.

Acknowledgments

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