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Introduction

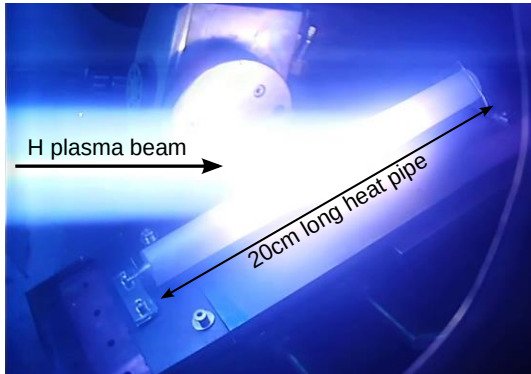


Figure 1: Visible light image of the heat pipe under plasma exposure in Magnum PSI

2cm diameter heat pipe with tantalum envelope and liquid lithium working fluid (Figure 1), procured by Sandia National Laboratories from Aavid/Thermacore, and a flat molybdenum plate used for reference thermal analysis. Crucial to the experiment was analysis of surface temperatures over as much of the target surfaces as possible. Although a near-infrared (NIR) spectro-pyrometer and mid-wavelength infrared camera are available on Magnum-PSI[3], their spatial coverage is limited to a small area of the targets. Additional IR thermography diagnostics were therefore needed, with the requirements of being able to operate in the limited space and 1-2T magnetic field inside the Magnum PSI superconducting magnet bore, and to measure temperatures in the range $\sim 900 - 1400$ °C over as much of the targets as possible. This paper presents the development of suitable low cost NIR thermography diagnostics based on commercial webcams.

Hardware

Commercial USB webcams (HP HD-4110; Fig. 2(a)) were used because of their compact size (~ 30 mm diameter, 70mm length) and because their control electronics do not contain inductive components susceptible to magnetic field effects. The cameras use 1920×1080 pixel CMOS sensors with a Bayer colour filter array and 8-bit digitisation, and provide a field of view of $\sim 67^\circ \times 41^\circ$ (horiz. x vert.). While the sensitivity of Si detectors at NIR wavelengths around $1\mu\text{m}$ is typically poor (often QE $< 5\%$), their use in this application is possible due to the high photon

In January 2018 experiments were carried out at Magnum PSI[1] to investigate the potential of radiatively coupled liquid metal heat pipes as the basis for an exchangeable, modular, high heat flux plasma facing component concept, as described by Makhankov et. al [2]. The experiment involved exposing two targets to a steady state hydrogen plasma beam and 1T magnetic field: a 20cm long,

flux of thermal emission at the relevant temperatures. The webcams were modified by removing the standard IR cut filter built in to the lens assembly (Fig. 2(b)), and an off-the-shelf 1" band-pass filter (ThorLabs FB1070-10) with 10nm bandwidth centred about $\lambda = 1070\text{nm}$ was instead used to define the measurement wavelength. The cameras also contained a voice-coil auto-focus mechanism which had to be removed to allow operation in magnetic fields (Figure 2(c)).

Data Acquisition

Custom Python software was written for data acquisition, using high-level video capture functionality in the OpenCV library to adjust camera settings and retrieve individual frames from the webcams. The webcams were configured for monochrome output and other settings left as the manufacturer's driver defaults. Due to the chosen software architecture the frame rate is very limited, typically to $\sim 1\text{Hz}$. For the present work this is not a problem due to the steady state nature of the experiment. The software provides a GUI with live temperature image view and plotting, data recording and the ability to raise temperature alarms via a serial port. The 8-bit image data are stored uncompressed for later analysis. The cameras were operated from a Windows 10 laptop, connected using 15m active USB extension cables which allowed the laptop to be remote from the experiment hall.

Calibration

Since webcams are optimised for qualitative visual imaging, the output digital image values are not linear with photon flux and the cameras' response curve shape must be calibrated to enable quantitative measurements. The webcams provide 8 exposure settings, and the response of each was individually calibrated by measuring a range of known NIR radiance from a variable temperature laboratory black body source (Isotech Pegasus R). The radiance within the filter pass band, ϕ , was calculated for each measurement, and curves relating this to the camera signal S then fitted. The results show that these cameras give a near-logarithmic response, after gamma correction. The calibration curves are therefore of the form $\phi = A \cdot 10^{\Gamma \cdot S^\gamma}$, where A is an exposure



Figure 2: Photographs of (a) one of the webcams, (b) and (c) modifications made for the magnum PSI experiments.

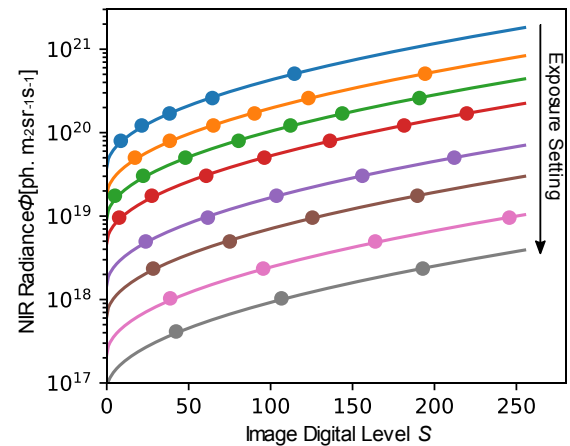


Figure 3: Calibration data points (circles) and fitted calibration curves (lines) for a single webcam at all exposure settings

dependent fit parameter and Γ and γ are fit parameters common to all settings. The calibration curves for one of the cameras are shown in figure 3. This shows a total linear dynamic range of $\sim 10^4$, with a temperature sensitivity range of 530°C - 1630°C assuming a grey body target with emittance $\varepsilon = 0.5$. Making use of this full dynamic range requires taking successive frames at each exposure setting, on a timescale shorter than variations in the temperature image being measured (~ 8 s) and combining them in post-processing. Since the emittances of the heat pipe and Mo plate were not well known, absolute temperature calibration was obtained by cross-calibration with an NIR spectro-pyrometer (FAR Associates FMPI), which measured the thermal emission spectrum from a small spot in the wavelength range $\sim 1175 - 1600$ nm. The spectral emittance used in the camera calibration was based on available data for polished material[4], multiplied by a constant to match the camera and pyrometer temperatures. Since the pyrometer measured a position on the targets where strong temperature gradients were observed, small uncertainties in the pyrometer spot position relative to the camera data ($\sim$ a few mm) result in relatively large uncertainty in the emittance and temperature errors of order 100°C. This is the dominant source of uncertainty in the webcam temperature measurements, and further checking & optimisation of the cross-calibration is ongoing.

Magnum-PSI Experimental Setup

A cut-away of the Magnum PSI target chamber showing the heat pipe experiment geometry is shown in Figure 4. Two of the modified webcams were installed 45° above the horizontal midplane looking down at the target holder from either side. For the heat pipe, this provided spatial coverage of the entire 20cm pipe length and up to 265° around the pipe circumference. The camera viewing geometry was calibrated using the Calcam code[5], which provided a mapping between image coordinates and position on the target surface.

Example Measurements

Figures 5(a) and (b) show calibrated photon flux images from the two webcams, showing the heat pipe at steady state under an estimated peak heat flux of ~ 8 MW/m² and 750W total power. Combining these two images using the spatial mapping and cross-calibrating with the

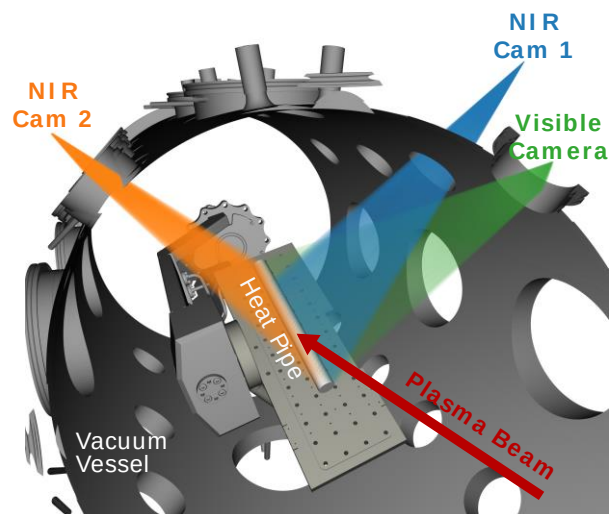


Figure 4: NIR and visible camera viewing geometry for the Magnum PSI heat pipe experiment. Images from the NIR cameras can be seen in figure 5, while an image from the visible camera is shown in figure 1.

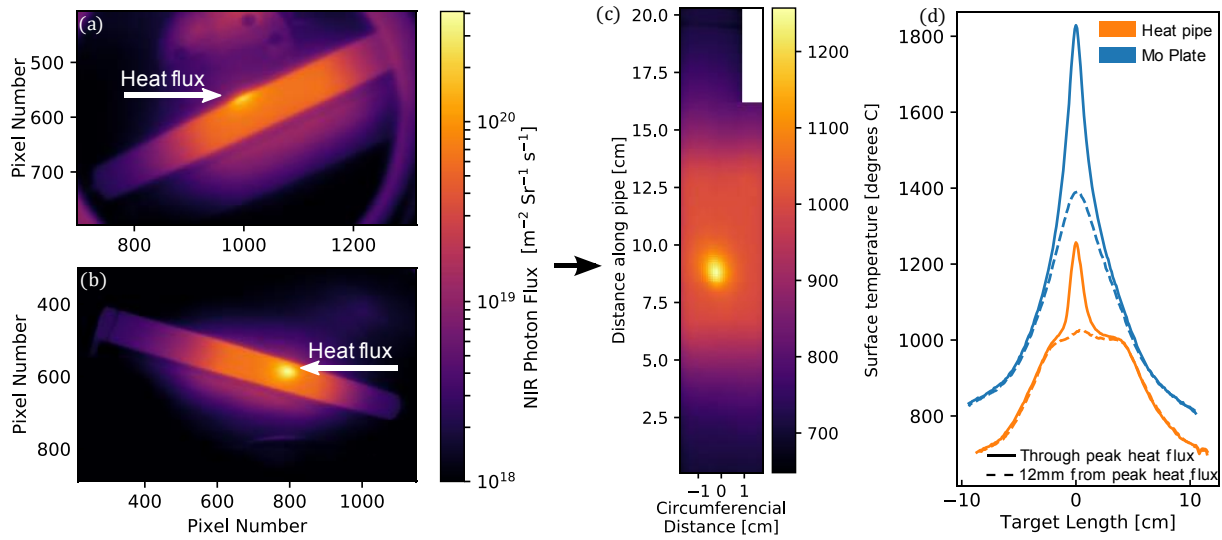


Figure 5: (a,b) calibrated photon flux images showing the heat pipe under plasma load (c) temperature map over the heat pipe surface, (d) 1D profiles along the heat pipe and solid Mo plate targets under identical load.

pyrometer, temperature maps over the heat pipe surface were obtained as shown in Fig 5(c). Where the views of the two cameras overlap, the temperature was obtained from a weighted mean of the values from the two cameras, with the weighting varying linearly from one camera to the other across the overlapping region. The white area in the upper right corner represents a region not viewed by either camera. Fig 5(d) shows 1D cuts through this temperature map along with comparable profiles from the flat plate under the same plasma conditions, taken both through the maximum heat flux position and 12mm to its side. The heat pipe exhibits a small hot spot within a ~6cm long near-isothermal region. This isothermal region is characteristic of the very high effective thermal conductivity of heat pipes, with the hot spot under the peak heat flux due to the limitation of heat conduction in the pipe's tantalum outer wall. Only ~6cm of the pipe was operating fully due to the low total power in this case. In contrast, the reference Mo plate shows strong temperature gradients over its entire surface. Analysis of the temperature data to determine the heat flux conditions and heat pipe performance in more detail is ongoing.

Acknowledgements

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