Smartphone Based Colour Ratio Pyrometry for Flame Temperature Measurement

Tejas Sakhalkar(18D170032)
Guide: Prof. Asish Kumar Sarangi
Co-guide: Prof. Neeraj Kumbhakarna

Department of Energy Science and Engineering
IIT Bombay

July 4, 2023

Goals and Major References

Goals

- Study the colour ratio pyrometry (CRP) technique
- Develop and validate the CRP procedure based on smartphone images
- Develop a product (possibly smartphone application) capable of analyzing flame temperature based on captured RAW images

Major references

- Anand Sankaranarayanan, Ph.D., IIT Bombay (2020)-'Droplet combustion studies on novel energetic propellants'
- Md. Saif Ansari, M.Tech., IIT Bombay (2022)-'Sooty Flame Temperature Measurement using Smartphone and DSLR Camera powered by Color Ratio Pyrometry Technique'

Table of Contents

Table of Contents

Pyrometry Techniques

- Intrusive
  - Thermocouple based: Flow obstruction, finite points measurement
  - Thin Filament Pyrometry: Flow obstruction, maintenance issues
- Non-intrusive
  - Rayleigh thermometry: Interference caused by particles in sooty flames[6]
  - CARS based: Expensive and only single point measurements[3]
  - Interferometry based: Expensive, complex and bulky setup[5]
  - Infrared Camera based: Conveneint, but less accurate
  - Soot Pyrometry

Two Colour Pyrometry

- Planck's Law for blackbody emission

$$I(\lambda,T) = \epsilon(\lambda)\frac{2\pi hc^2}{\lambda^5(e^{\frac{hc}{\lambda k_B T}} - 1)} \quad (1)$$

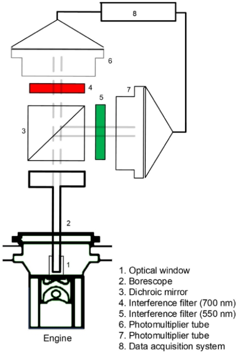
- Hottel and Broughton Model

$$\epsilon_\lambda(KL,\lambda) = 1 - e^{\frac{-KL}{\lambda^\alpha}} \quad (2)$$

  - KL= Optical thickness
  - α= soot dispersion coefficient

- Combining both-

$$I(\lambda,T) = 1 - e^{\frac{-KL}{\lambda^\alpha}}\frac{2\pi hc^2}{\lambda^5(e^{\frac{hc}{\lambda k_B T}} - 1)} \quad (3)$$



Example implementation of Two Colour Pyrometry taken from [2][7][4]

- Narrow band technique
- Passive, fast response time and reliable

Color Ratio Pyrometry

- Signal detected on a pixel S_f is NOT the intensity at a specific wavelength

$$S_F = 2\pi hc^2\tau \int_{\lambda_1}^{\lambda_2} \frac{\epsilon(\lambda)\eta(\lambda)}{\lambda^5(exp(hc/\lambda k_B T) - 1)}\, d\lambda \tag{4}$$

- η measures the contribution of intensities of different wavelength towards the signal (propery of a sensor, calibration required)
- Wide band technique
- The ratio of these signals is a function of T and soot dispersion coefficient α when ϵ is taken to vary as $\lambda^{-\alpha}$

$$\frac{S_F 1}{S_F 2} = \frac{\int_{\lambda_1}^{\lambda_2} \frac{\epsilon(\lambda)\eta_{F1}(\lambda)}{\lambda^5(exp(hc/\lambda k_B T) - 1)}\, d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{\epsilon(\lambda)\eta_{F2}(\lambda)}{\lambda^5(exp(hc/\lambda k_B T) - 1)}\, d\lambda} \tag{5}$$

Table of Contents

Camera Sensors

CCD and CMOS sensors as wide (visible range) band pyrometers

Feature	**CCD(Charge-Coupled Device)**	**CMOS(Complementary Metal-Oxide-Semiconductor)**
Sensitivity	Higher sensitivity, better performance	Lower sensitivity, but significant advancements made
Noise Levels	Lower noise levels, cleaner images	Higher noise levels, but improved with noise reduction techniques
Power Consumption	Higher power consumption	Lower power consumption, more power-efficient
Speed	Slower readout and processing	Faster readout and processing
Application Range	High-end professional cameras	Consumer electronics, smartphones, and more

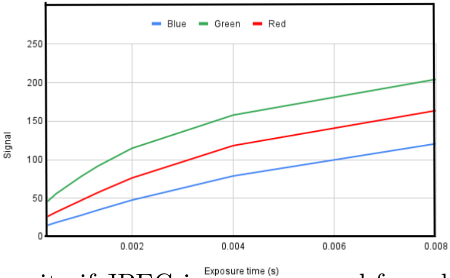
Smartphone Camera

Google CameraAPI for Android to take images: v2 includes RAW image capabilities

Parameter	**Details**
ISO	Camera sensor sensitivity to light. Higher values for better low-light performance, but more noise. Lower values require more light for exposure.
Shutter Speed	Duration of the camera's shutter being open. Fast speeds freeze motion, slow speeds create motion blur or long-exposure shots.
Aperture	Opening of the camera's lens that controls light and depth of field. Wider aperture lets in more light and creates shallow depth of field.
White Balance	Adjustment of color response for accurate reproduction under different lighting conditions. Corrects color casts caused by varying temperatures.
Focus Modes	Different focus settings: Single Autofocus, Continuous Autofocus, Manual Focus, and Automatic Autofocus.

Importance of RAW for CRP

Formats: JPEG, RAW, TIFF, DNG



Non linearity if JPEG images are used for calibration

63	1023	63	1023
258	64	266	64
64	1023	63	1023
273	65	263	64

Sample RAW bayer data from a 16 pixel image:
Green is at black level with thermal noise.
Blue is saturated or at white level

Sensors Used

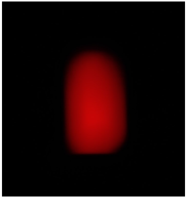
Number	Device	Sensor	Specifications
1	One Plus 9RT 5G	Sony IMX766	50 MP resolution 1.67" image sensor
2	Realme X3 Superzoom	Samsung GW1 sensor	64 MP resolution 1/1.72" image sensor
3	Motorola Moto G82	Samsung S5KJN1	50 MP resolution 1/2.76" image sensor
4	Raspberry Pi Camera Module V2	Sony IMX708	12 MP resolution 1/1.3" image sensor

Table of Contents

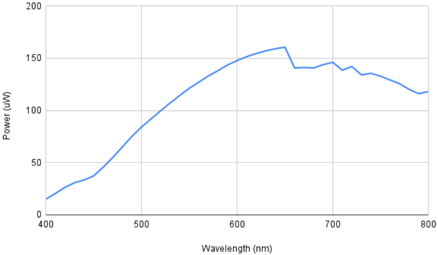
Monochromator and Power Meter

Holmarc HO-SP-SQR200F and HO-OPM-01UV
Readings at 10 nm intervals from 400 to 700 nm

Read DNG image to 2D array in Matlab → Crop part of image with monochromatic light required for analysis → Split array into R, G, B as per Bayer pattern and take averages → Export averages and normalize with the power meter data



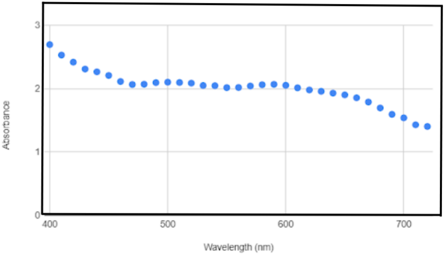
Monochromator light captured by Sensor 2



Variation of power of light emitted by monochromator with wavelength

ND filter

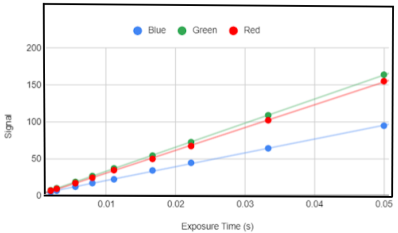
- Used to reduce saturation of images of monochromatic light because of very bright source

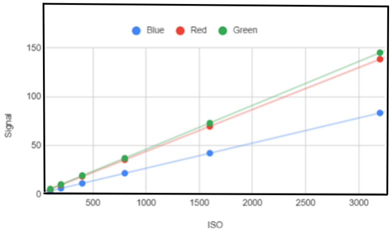


Absorbance of ND filter (log scale)

- Need to include the wavelength dependent transmittance factor in calibration
- Discarded as alternative solution by changing aperture of monochromator was found

Linearity

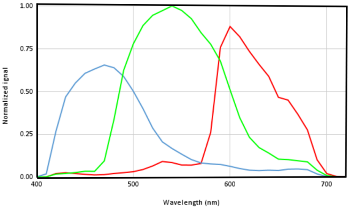




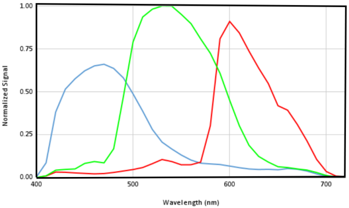
Variation of signal with variation in exposure time (ET) and ISO

Read DNG image to 2D array in Matlab → Split array into R, G, B as per Bayer pattern and take averages → Take average of all non-zero elements in the arrays → Repeat the procedure by changing ET or ISO keeping the frame constant

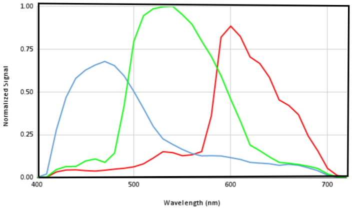
Spectral Response Curves



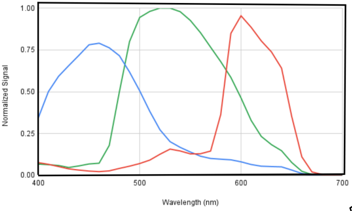
Spectral response curve of sensor 1



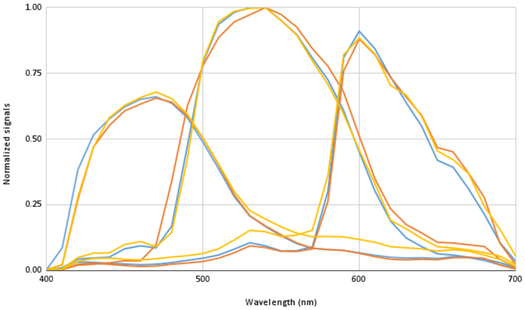
Spectral response curve of sensor 2



Spectral response curve of sensor 3



Spectral response curve of sensor 4



3 SRCs of smart phone cameras with different sensors compiled in one graph

- Possibility of coming up with a commmon SRC
- Limitations of monochromator, sharp edges in SRC

Blackbody calibration

- Validation of CRP on blackbody emissions

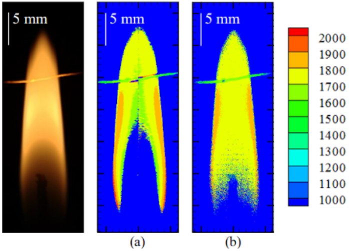
Calsys 1500BB furnace

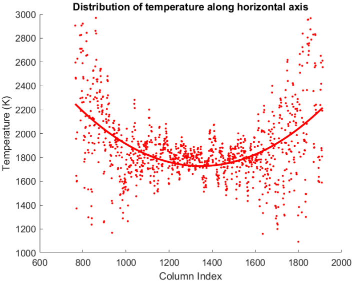
- Because of heater issues, couldn't collect data

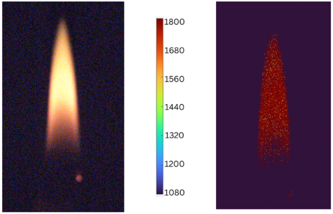
Thermocouple Measurements

- One more validation method, Different types of thermocouples used- unsheathed K, sheathed N and unsheathed B
- K and N type thermocouples calibrated in Dry block setup (Fluke Calibration 9173) using DT 9828 DAQ
- The maximum observed error of 5 degrees Celsius at the highest temperature of the calibrator, 700 degrees celsius, but, K and N type thermocouples saturated below flame temperature
- B type thermocouple used to take the temperature measurements of flat flame

Candle Flame

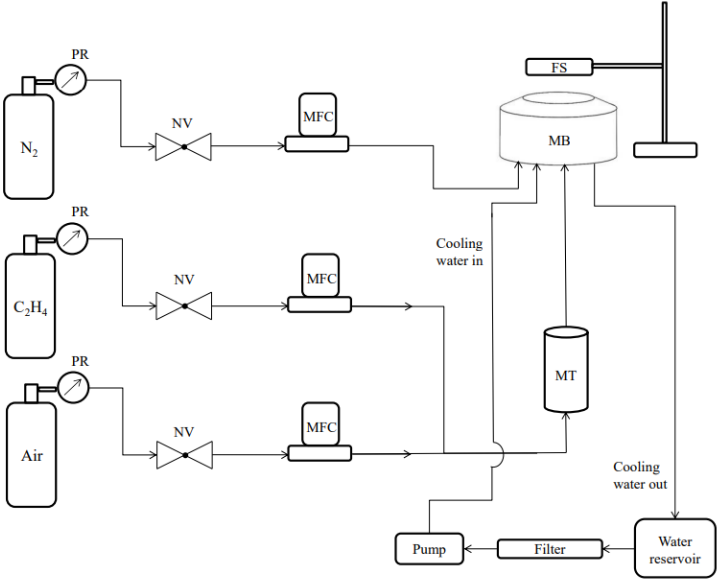






Further, using Abel inversion, radial temperature profile can be found

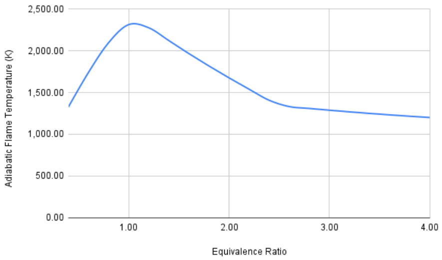
Flat Flame


PR
N_2
NV
MFC
PR
C_2H_4
NV
MFC
PR
Air
NV
MFC
FS
MB
Cooling water in
MT
Cooling water out
Pump
Filter
Water reservoir

Flat Flame

Experimental Setup

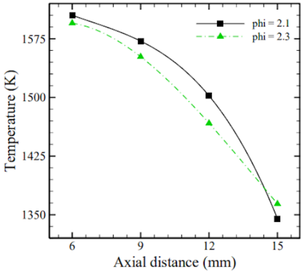
Flat Flame

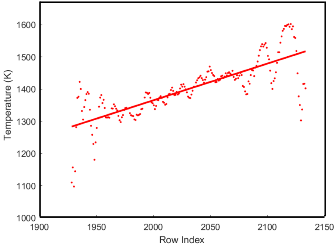


NASA CEA simulation results and comparison with actual experimental data

Equivalence Ratio	**Median temperature along vertical axis (in K)**	**Mean temperature along vertical axis (in K)**	**Expected adiabatic flame temperature**
2.1	1420	1425	1550
2.3	1395	1400	1450
2.5	1375	1385	1400

Flat Flame



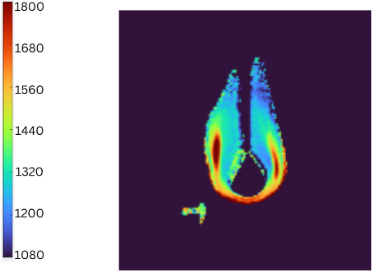


Variation of temperature along vertical axis of flat flame

Change in flame structure with variation in Nitrogen flow rate

Droplet Flame

- Coal tar pitch melted using a hotplate
- Quartz rod dipped in it
- The rod inserted inside the combustion chamber and ignited using



Droplet Flame

Droplet flame and temperature analysis of RP1 surrogate fuel

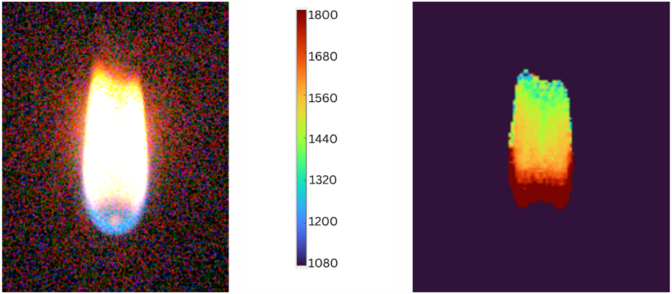


Table of Contents

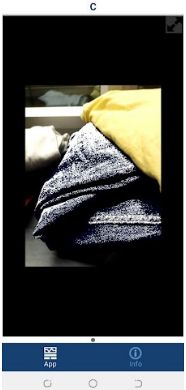
Different Platforms

- Different platforms- Android Studio Code, Matlab Simulink: Android Support Package, MIT App inventor, Matlab App Designer
- Matlab finalized, as all the codes written in Matlab because of huge matrices
- Issue with Matlab exported code integration in Android Studio Code

Application Developed

Mathematics operations performer (Developed on Android studio)

Camera preview app (Developed on Android studio)



Colour detection app (Developed using Matlab Simulink support package)

Checklist app (Developed using MIT app inventor)

Application Developed

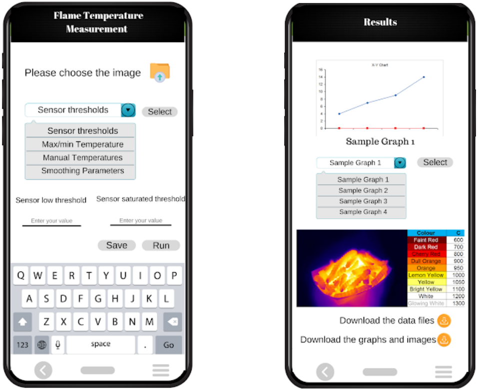
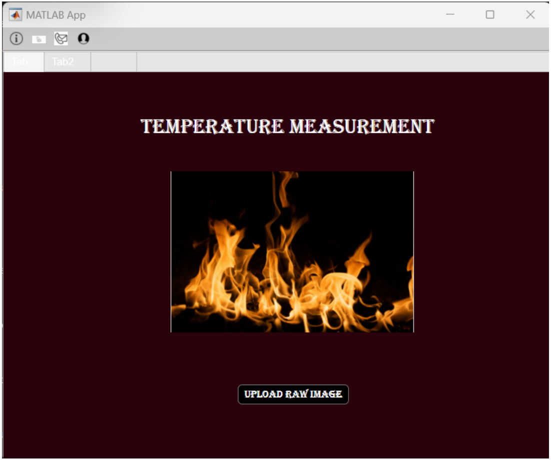


Figure: Future possibility of advanced Android App

Final Application



Final application developed on MATLAB appdesigner

RPI Product

- Need to calibrate every new sensor in case of smartphone
- Because of supply chain issue, RPi with lower specifications was used
- Enough processing power to take images, but not to process them
- Images transferred to desktop and processed
- Once the issue is resolved, the application can be integrated in RPi, too

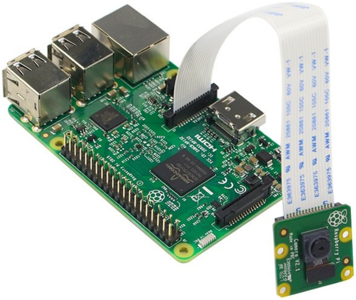


Table of Contents

Conclusions and Future Work

- Successful development of CRP procedures for smartphone camera images
- Accurate flame temperature analysis with average error <80K
- Reliable results matching with DSLR camera-based CRP technique
- User-friendly and affordable Matlab app-based product
- Potential for future extension to analyze asymmetric and non-sooty flames
- Addressing calibration hurdle with RPi-based product for mass production
- Future possibilities: Abel inversion algorithm for radial temperature distribution and measuring soot fraction in flames
- Contributions to the field of flame temperature analysis and practical applications
- Encouragement for further research and development in smartphone camera-based CRP techniques

Bibliography I

[1] Md. Saif Ansari. "Sooty Flame Temperature Measurement using Smartphone and DSLR Camera powered by Color Ratio Pyrometry Technique". MA thesis. Department of Mechanical Engineering Indian Institute of Technology, Bombay Powai - 400076, Maharashtra, India: Indian Institute of Technology, Bombay, June 2022.

[2] Martin H. Davy et al. "Two-Colour Pyrometry Measurements of Low-Temperature Combustion using Borescopic Imaging". In: *SAE WCX Digital Summit*. SAE International, Apr. 2021. DOI: https://doi.org/10.4271/2021-01-0426. URL: https://doi.org/10.4271/2021-01-0426.

[3] G Hartung, J Hult, and C F Kaminski. "A flat flame burner for the calibration of laser thermometry techniques". In: *Measurement Science and Technology* 17 (Aug. 2006), p. 2485. DOI: 10.1088/0957-0233/17/9/016. URL: https://dx.doi.org/10.1088/0957-0233/17/9/016.

[4] Shawn A. Reggeti, Ajay K. Agrawal, and Joshua A. Bittle. "Two-color pyrometry system to eliminate optical errors for spatially resolved measurements in flames". In: *Appl. Opt.* 58 (Nov. 2019), pp. 8905–8913. DOI: 10.1364/AO.58.008905. URL: https://opg.optica.org/ao/abstract.cfm?URI=ao-58-32-8905.

[5] Chandra Shakher and Anil Kumar Nirala. "A review on refractive index and temperature profile measurements using laser-based interferometric techniques". In: *Optics and Lasers in Engineering* 31.6 (1999), pp. 455–491. DOI: https://doi.org/10.1016/S0143-8166(99)00037-8. URL: https://www.sciencedirect.com/science/article/pii/S0143816699000378.

[6] Gavin Sutton et al. "A combustion temperature and species standard for the calibration of laser diagnostic techniques". In: *Combustion and Flame* 147 (2006), pp. 39–48. DOI: https://doi.org/10.1016/j.combustflame.2006.07.013. URL: https://www.sciencedirect.com/science/article/pii/S0010218006001842.

[7] J. Thevenet, M. Siroux, and Bernard Desmet. "Brake disc surface temperature measurement using a fiber optic two-color pyrometer". In: Jan. 2008. DOI: 10.21611/qirt.2008.02_12_14.

Thank You for Your Attention!