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Research Paper

High-speed camera thermometry of laser droplet generation

Benjamin Bizjan *, Alexander Kuznetsov, Andrej Jeromen, Edvard Govekar, Brane Širok

Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia

HIGHLIGHTS

- High-speed thermometry was applied to the laser droplet generation process.
- Droplet temperature was measured with an excellent spatial and temporal resolution.
- Pendant droplets cool more rapidly than detached droplets due to heat conduction.
- Droplet oscillation dynamics are well characterized by its area and contours.

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ABSTRACT

This paper presents a high-speed thermal imaging method using a visible light camera, with application to the laser droplet generation process (LDG). In the experiment, a nickel wire-end was exposed to a collimated laser beam, and the subsequent process of wire melting, pendant droplet formation and its detachment were recorded by a high speed camera. Instantaneous temperature fields of the metal surface were calculated from the imaging data and were characterized by a very good spatial and temporal resolution (200 × 400 pixels at 13,837 frames per second). The droplet temperature could be accurately calculated between the melting point of nickel (1455 °C) and approximately 1950 °C, where image saturation started to occur. The remaining pendant droplet was shown to cool much more rapidly than the detached droplet, which is due to the heat conduction to the solid wire. Except for the time immediately after the droplet separation, the temperature distribution across the melt droplets was found to be quite uniform. Apart from the possibility of temperature field calculation, it was also demonstrated that the high-speed images of the LDG process can accurately capture contours and oscillation dynamics of melt droplets.

1. Introduction

Precise high-speed temperature measurements are very important in many technological processes characterized by high material velocities or short duration. An example of such a process is the laser droplet generation (LDG), which can be used for many different technological applications such as joining [1,2], 3D structuring [3], repair of worn metal surfaces, microforming and microcasting [4]. Due to the presence of multiple flow phases and the very high temperatures of melt droplets (often in excess of 2000 °C), only non-contact methods can be used to measure the temperature. Non-contact temperature measurements are most commonly performed by pyrometers or infrared cameras [5–9], but these devices have several operating limitations. Pyrometers are only capable of single-point temperature measurements, while the infrared cameras, though capable of measuring instantaneous temperature fields, are not well-suited for application in high-speed processes due to their limited spatial resolution and dynamic response as well as the high cost.

Since the LDG process is characterized by very high temperatures, the solid and liquid metal phases glow, emitting a high luminous flux. With that said, the temperature of the process can be measured by means of high-speed visible light cameras, which are characterized by much higher recording rates and image resolution than their infrared counterparts. The concept of using standard CCD and CMOS digital cameras for temperature measurement has attracted several authors so far, especially in the area of metallurgy [10–12] and combustion studies [13–15]. The studies [12–15] employed color (RGB) cameras with the so-called two-color approach, where the ratio of image brightness in two different color channels was used to determine the temperature. Yan

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* Corresponding author.

E-mail addresses: benjamin.bizjan@fs.uni-lj.si (B. Bizjan), alexander.kuznetsov@fs.uni-lj.si (A. Kuznetsov), andrej.jeromen@fs.uni-lj.si (A. Jeromen), edvard.govekar@fs.uni-lj.si (E. Govekar), brane.sirok@fs.uni-lj.si (B. Širok).

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Nomenclature

A	droplet projection area, $\mathrm{m^2}$
B_λ	spectral radiance, $\mathrm{W\,sr^{-1}\,m^{-3}}$
C	calibration constant, –
c	speed of light, $\mathrm{m\,s^{-1}}$
D_{pdr}	pendant droplet diameter, m
D_{dr}	detached droplet diameter, m
D_{pdr}	remaining pendant droplet diameter, m
G	normalized image gray level, –
h	Planck constant, J K
k	camera sensor sensitivity, $\mathrm{lux^{-1}\,s^{-1}}$
k_{B}	Boltzmann constant, $\mathrm{J\,K^{-1}}$
P	laser power output, W
T	temperature, °C
T_{K}	absolute temperature, K
T_{py}	pyrometer-measured temperature, °C
t	time since the trigger activation, s
t^*	time since the detachment pulse, s
t_{E}	camera exposure time, s
Y	camera sensor quantum efficiency, –
ε	emissivity, –
λ	wavelength of emitted light, m
$\Delta\lambda$	discrete wavelength step for integration, m
σ_{S}	Stefan-Boltzmann constant, $\mathrm{W\,m^{-2}\,K^{-4}}$

and Li [16] proposed and evaluated an algorithm and a system for two-color temperature measurement, while Ma and Zhang [17] discussed the limitations of the method due to the image saturation. A different approach was taken by Chen et al. [10], Zhang et al. [11] and Bizjan et al. [18,19] who used a measurement system with a monochrome camera.

There are certain advantages of the two-color method over the monochrome method, namely the lack of need for the reference point temperature measurement and a reduced measurement error in the case of a non-constant spectral emissivity [16]. On the other hand, the two-color method suffers from a more narrow temperature measurement range. Also, most of today's color cameras use a Bayer filter mosaic array on top of the imager, which effectively reduces both the image resolution and light sensitivity when compared to the monochrome camera of the same pixel count [11]. This becomes particularly problematic in high-speed applications where image resolution is already limited by high acquisition rates, and it is often difficult to provide sufficient lighting due to extremely short exposure times required for capturing sharp images. For these reasons, the monochrome visible-light cameras seem to be best suited for high speed temperature measurements. Using a monochrome high-speed camera, Bizjan et al. [18,19] recorded the mineral wool fiberization process and was able to calculate temperature fields with a high spatial and temporal resolution, and a good accuracy. In the present paper, this method will be applied to the LDG process to accurately represent the typical thermal and hydrodynamic phenomena of this promising manufacturing process.

2. Theoretical background and methodology

Laser-molten nickel droplets can reach temperatures in excess of 2000 °C, meaning a substantial fraction of light is emitted in the part of the spectrum between 400 nm and 1000 nm, where standard CCD and CMOS camera sensors are normally most sensitive for electromagnetic radiation. Due to a very short duration of the LDG process, high-speed visible light cameras are well suited to capture the process dynamics while achieving a good image resolution.

In this manuscript, experimental temperature measurements were performed by a high-speed monochrome camera and a temperature calculation algorithm proposed in our previous publications [18,19]. This section will provide a brief overview of the method. The input information required for temperature calculation is the normalized image gray level 0 (black color) $\leqslant G \leqslant$ 1 (white color), which can be assumed to be proportional to the camera sensor voltage response due to the incident light. The following set of equations was proposed for temperature calculation [18,19]:

$$T_K = C\sqrt[4]{\frac{G}{k\cdot\eta(T_K)\cdot t_E\cdot\sigma_S}}, \tag{1}$$

$$\eta = \frac{\int_0^\infty Y(\lambda)B_\lambda(\lambda)d\lambda}{\int_0^\infty B_\lambda(\lambda)d\lambda} \approx \frac{\sum_{0.4\mu m}^{1\mu m} Y(\lambda)B_\lambda(\lambda)\Delta\lambda}{\frac{2}{15}\frac{\pi^4 k_B^4}{h^3c^2}}, \tag{2}$$

$$B_\lambda = \frac{2hc^2}{\lambda^5}\frac{1}{\exp(hc/\lambda k_B T_K) - 1}. \tag{3}$$

In Eqs. (1)–(3), T_{K} is the absolute temperature in [K], k is the camera sensor sensitivity, t_{E} the camera shutter time, η the light efficacy, Y the sensor quantum efficiency, λ the wavelength of light and B_λ the spectral radiance. The physical constants are as follows: $\sigma_{\mathrm{S}} = 5.67 \cdot 10^{-8}\ \mathrm{W m^{-2}\,K^{-4}}$ (Stefan-Boltzmann constant), $k_{\mathrm{B}} = 1.381 \cdot 10^{-23}$ J/K (Boltzmann constant), $h = 6.626 \cdot 10^{-34}$ J s (Planck constant), $c = 2.998 \cdot 10^8$ m/s (speed of light in vacuum).

The constant C depends on the measurement set-up, and implicitly contains all the variables which are not directly measured or known, but can be assumed to remain constant during the experiment. These variables include, but are not limited to, the surface emissivity ε (proportional to C^4), lenses aperture setting, focal distance and internal light absorption. C is obtained from Eq. (1) by calibration to a surface with a known reference temperature and the corresponding image gray level at that location. In our case, the reference temperature was measured by a pyrometer.

In Eq. (1), the glowing surfaces are treated as gray bodies, i.e. the emissivity is assumed to be constant with temperature and with wavelength of emitted light. Such assumption is justified due to relatively narrow wavelength ranges in which visible light cameras operate, and consequently also narrow temperature measurement ranges. Using the above-presented algorithm, the temperature fields can be obtained by element-wise transformation of image gray level matrices.

3. Experimental set-up

The experimental set-up comprised the laser droplet generation (LDG) system and the temperature data acquisition system (Fig. 1).

The LDG system consists of a pulsed Nd:YAG laser source and an LDG head. The LDG head is used to shape a collimated beam into an annular ring, to guide the beam coaxially with the vertically fed metal wire and to focus the annular beam at the wire-end along its circumference [6]. The LDG process runs in two sequential phases, i.e. a pendant droplet formation (Fig. 2a–c) and pendant droplet detachment phase (Fig. 2d and e). In the pendant droplet formation phase, a wire-end is melted by a pendant droplet