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ON MEASURING VELOCITY AND TEMPERATURE IN LEAKAGE FLOWS OF OIL FREE ROTARY POSITIVE DISPLACEMENT MACHINES

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ABSTRACT:
One of the main issues affecting reliability and efficiency of rotary oil free positive displacement machines (PDM) is the size of the clearance gaps between the rotating and stationary parts of a machine. It is desired to reduce these gaps in order to improve efficiency but due to thermal growth these can become too small and cause catastrophic failure. This is one of the topics that remains largely unsolved as the physics of the flow within this gap in operation is not fully known. To fully understand the physics of this flow and to improve reliability and efficiency of PDMs, it is required to obtain the velocity and temperature fields of the leakage in clearance gaps, but it is challenging to obtain them during the operation of the machine. This study focuses on developing an experimental setup that can measure the velocity and temperature fields at the variety of operating conditions. This study is a part of the project "SECRET" (Smart Efficient Compression, Reliability and Energy Targets) supported by The Royal Academy of Engineering (RAEng) and Howden Compressors. National Instrument-based data acquisition system is designed to measure and control machine operating parameters such as pressure, temperature, flow, power, and speed. The particle image velocimetry (PIV) technique is used for velocity field measurement with the provision of optical access to the clearance gaps through a special glass window. Similarly, for measurement of the temperature field, the Planar laser-induced fluorescence (PLIF) technique is selected based on a feasibility study carried out earlier. High-speed infrared thermography is chosen to measure the operational surface temperature of rotary elements. Experimental results obtained from this setup will provide data for analysis of physics of aerothermal behaviour in clearance flows of PDMs, which will be benchmark case for CFD validation.

Keywords: *Velocity field, Temperature field, Leakage flows, PIV, PLIF, Infrared thermography*

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1. INTRODUCTION

In rotary positive displacement machines rotating parts are enclosed inside the stationary part known as casing. It is always necessary to maintain the gap between rotating and stationary part to achieve reliable operation of the machine. During operation of the machine, flow takes place through these clearance gaps, they are known as leakage flows. Figure 1 shows the location of various leakage paths present in a rotary screw machine and two-lobe roots blower. Six different internal clearance paths are identified by Fleming[1] inside the helical screw compressor. Quantitative effect of each leakage on volumetric efficiency is presented as well. Reliability and performance are functional characteristics of the compressor that are strongly dependent on the operating clearances. Clearance height and operating parameters can directly affect the volumetric efficiency and Isentropic efficiency of the machine[2]. The flow field inside these clearances has a complex structure due to a very small flow path, rotation of rotor and pressure difference across the gap. This complex flow is captured by Sachs[3] using schlieren method in static prototype of rotor and housing gap, that gives a clear idea of presence of complex flow phenomena inside the clearance in a stationary condition.

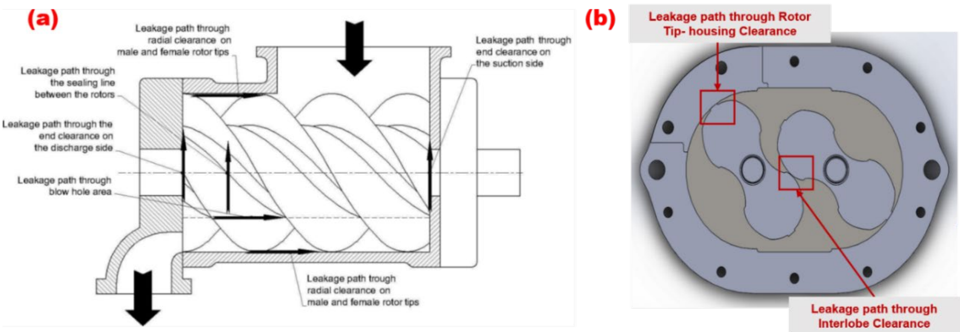

Fig.1. (a) Leakage paths in screw machine [4] (b) Leakage paths in Roots Blower[1]

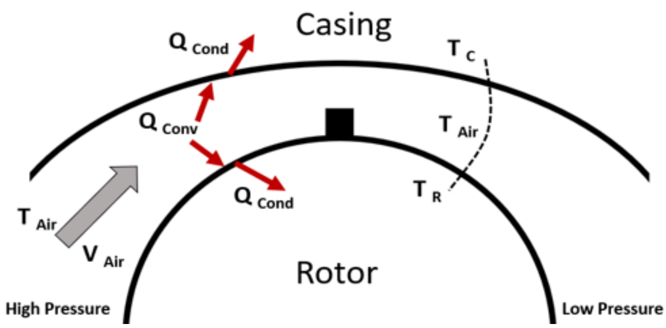

Fig.2. Leakage flow and heat transfer between Rotor Tip and Housing[2].

[1] Image generated by the authors
[2] Image generated by the authors

In PDMs discharge temperature increases with discharge pressure. In oil-free machines, gas present in the pressurized chamber at higher temperature leaks through clearances to low-pressure region and heat transfer can take place from fluid to solid. It is illustrated in Figure 2 in the form of 2D rotor tip – housing clearance.
Various methods are studied to obtain the velocity and temperature flow field experimentally, and some useful techniques are identified. Particle image velocimetry (PIV) has a ability to get velocity field[5, 6] while Planar laser-induced fluorescence (PLIF) has the potential to measure the temperature field in the leakage gap during the running condition of the machine. However, this technique is not used in the past for similar application, so feasibility study of PLIF is carried out.
In present study, three different techniques PIV, PLIF and Infrared thermography, are selected based on their non-intrusive nature to produce aerothermal behaviour of flow in clearance. These all are imaging techniques and able to provide images of the velocity field, temperature field in the gas flow and surface temperature. Detailed design of data aquation system, selection and design of optical components for PIV and PLIF and IR thermography is presented. The setup of these methods consists of basic devices of two types. The first is functional such as the camera, the laser, synchronizer, software and seeding particles for PIV. The second type is optical devices such as laser arm, sheet optics and lens.

2. EXPERIMENTAL SETUP DEVELOPMENT

Proper data acquisition system is needed which can measure and control operating parameters of the machine to perform experiment using any methods. For that National instruments based DAQ system is developed along with PIV, PLIF and IR thermography setup.

2.1. Data acquisition system

Figure 3 shows schematic diagram of Roots blower test rig. The Oil-free Roots blower URAI-22 from Howden is used. Roots blower is connected with variable speed electric motor by pulley transmission system to run at various operating conditions, and Roots blower can run up to 2700 RPM based on current pulley ratio. To monitor and control operating parameter of the machine, pressure, and temperature sensors at suction (P1, T1), discharge (P2, T2) and at Orifice (ΔP, T3) are installed. Shaft encoder and torque meter is used to measure speed and power of roots blower. Detailed specification of selected sensors is listed in Table 1. Flow of the machine is measures using Orifice. Speed of machine is adjusted by variable frequency drive connected with motor. The ball valve is installed in the discharge line of the machine to maintain require discharge pressure. To increase the discharge pressure, discharge valve needs to close manually and with increase in discharge pressure, the discharge temperature of the machine also increases. In the present study, discharge pressure is not exceeding 2 barg. All sensors are connected with National instrument cRIO-9056 using appropriate NI modules, respective modules used for sensors are shown in Table 2. Various voltage supplies such as 24V, 12V,10V and 5V are used to power up cRIO, pressure transducers, torque meter and shaft encoder, respectively. LabView FPGA program is developed to record real time data.

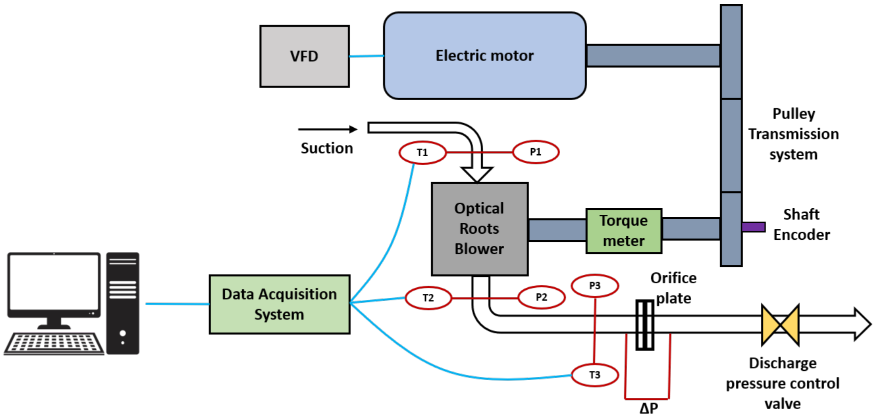

Fig.3. Schematic diagram of Roots blower test rig[3]

Table 1. Sensor specification

Parameters	Instrument	Specification
Speed, N	Shaft Encoder (BHG 16.25W.3600-B2-5)	3600 TTL pulses per revolution Accuracy= ±10%
Torque, T	TP-5 KMCB torque meter (strain gauge transducer)	Max capacity: 50Nm, Range = 0 - 6000 rpm, Supply volt=10v dc, Accuracy= 0.25 % of max capacity
Inlet pressure, P1	PMP5026 pressure Transducer	Operating range = 3.5bar(abs) Excite voltage=12-16V dc, Output Voltage = 0-10 V Accuracy = ±0.2% FS.
Inlet temperature, T1 Outlet temperature, T2 Orifice plate inlet Temp, Top	Platinum Resistance Thermometer	Range= -75°C to 250 °C, Accuracy= ±0.5 °C
Outlet pressure, P2 Orifice plate inlet press, Pop	PMP5026 pressure Transducer	Operating range =15 bar (abs) Excite voltage=12-16V dc, Output Voltage = 0-10 V Accuracy = ±0.2% FS,
Orifice plate differential pressure, DP	PMP5026 pressure Transducer	Pressure diff = 0.5 bar Excite voltage=12-16V dc, Output Voltage = 0-10 V Accuracy = ±0.2% FS.

Table 2. Specifications of the NI modules

NI Module	Measuring instrument

[3] Image generated by authors

cRIO-9056, 1.33 GHz Dual-Core, Artix-7 75T FPGA, 8-Slot, RT, Non-XT	cRIO
NI 9401 8-Channel, 100 ns, TTL Digital Input/output Module	Shaft Encoder (Speed)
NI 9201 Spring Term, +/-10 V, 12-Bit, 500 kS/s, 8-Ch AI Module	Pressure sensors
NI 9216 Spring, 8-Ch RTD, PT100, 24-bit, 50S/s/ch AI module	RTD
NI 9237 4-Ch 50 kS/s/Ch, 24-Bit Bridge AI Module	Torque meter

2.2. Particle image velocimetry (PIV) setup

Particle image velocimetry (PIV) is an optical method of flow visualization. It is used to obtain instantaneous velocity measurements and related properties in fluids. For that optical access of clearance gap is required. For optical access, fused silica glass is the best suitable material for our application. Figure 4 (a) shows a complex shape of the optical Glass manufactured from the Fused silica. As shown in Figure 4 (b) & (c), Optical access from radial direction and side of the Roots blower (upper left portion in Figure 1(b)) is provided to visualize a flow in clearance gap between rotor tip and housing. A thin gasket is used between metal and Glass surface to avoid any direct contact to reduce risk of cracking in the Glass at higher working temperature. Glass is kept tight using an external metal plate to eliminate leakage through glass and metal mating surfaces.

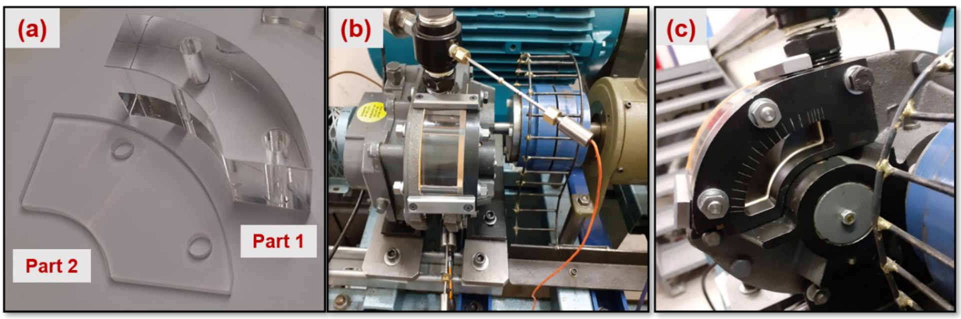

Fig.4. (a) Optical element from Fused silica Glass (b) Radial optical access of Roots blower (c) optical access from side of Roots blower[4]

In PIV experiments the fluid is seeded with tracer particles, for sufficiently small particles, are assumed to faithfully follow the flow dynamics. The fluid with entrained particles is illuminated by laser and motion of those particles are captured by cameras. The motion of the seeding particles is used to calculate speed and direction (the velocity field) of the flow being studied. Schematic of the designed PIV setup is shown in Fig. Dual pulse Litron Bernoulli laser with 532nm wavelength is selected. Its maximum output energy is about 200mJ per pulse at frequency of 15Hz. This laser has a pulse-to-pulse energy stability less

[4] Image generated by authors

than 2% RMS. For imaging, HiSense zyla 5.5 MP camera, 8 bit and 40 fps having resolution of 2560 by 2160 pixels has been chosen. K2 DistaMax standard objective is used to get better magnification of small clearance gap. High performance synchronizer is used along with encoder input for cyclic synchronizer to trigger laser and image at same time precisely. Long light guide arm (2100mm) suitable for 532 and 266nm wavelength is selected to transfer laser beam from laser head to area under study. In addition, laser sheet optics is required to convert laser beam to laser sheet, for that UV/VIS Parallel Light Sheet Optics and beam waist adjuster are implemented. In this study DEHS (Di-Ethyl-Hexyl-Sebacic) particles as a tracer, it will be seeded using Liquid Seeder (type FT700CE).

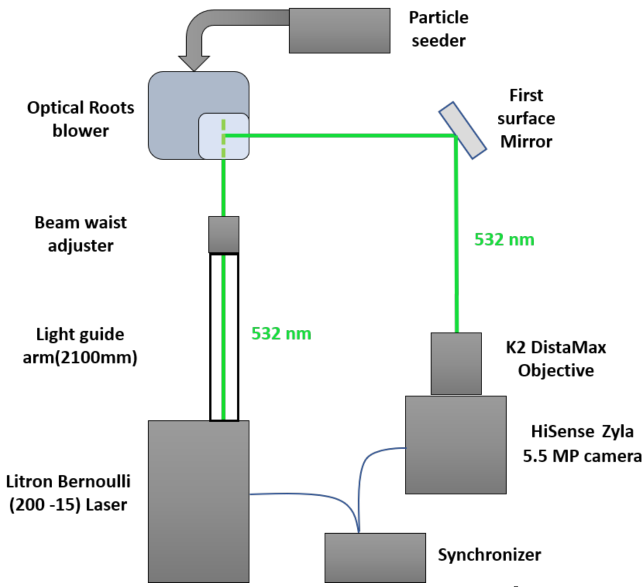

Fig.5. PIV experiment setup layout[5]

2.3. Planar induced laser fluorescence (PLIF)

With the advancement of computers and processing power, it is possible to process large Laser-induced fluorescence (LIF) is a technique for nonintrusive visualization of concentrations in the mixing of gaseous and liquid flows and for gas-temperature imaging. Basic concept is same as PIV, but in PLIF fluorescence particles are used instead of tracer particles. Upon excitation by an ultraviolet light/laser source, tracer molecules gain energy which is sometimes dissipated by photon emission. A camera collects these photons, and the resulting signal is quantified according to its dependencies on any relevant flow parameters.

The total collected LIF signal (S_{LIF}) can be described by the following relationship,

[5] Image generated by authors

$$S_{LIF} = \eta_{opt} \left(\frac{E_{pulse}\, \lambda}{Ahc} \right) V_{pix} \nu_{tracer} \sigma_{abs} \phi_f \qquad (1)$$

Where η_{opt} stands for the efficiency of the collection optics and incorporates factors such as the solid angle of the detector lens and the spectral responsivity of the detection system. E_{pulse} is local laser fluence, h is plank constant, c is the speed of light in vacuum, λ is the wavelength and A is laser sheet area. Altogether the bracketed term represents the number of excitation photons per laser-sheet cross-sectional area. The product of the size of the imaged volume (V_{pix}) along the laser sheet propagation times the tracer number density (ν_{tracer}) gives the number of tracer molecules available for excitation. The last two terms, the absorption cross-section (σ_{abs}) and the fluorescence quantum yield (φ_f) account for the photophysical dependencies of the fluorescence signal and represent the probability of absorption and the efficiency of fluorescence emission respectively. The particular tracer class displays strong absorption in the UV and high signal sensitivity to temperature and oxygen concentration.

The two-colour detection approach (2-colour LIF) requires the illumination of the seeded volume and the subsequent detection of the emitted fluorescence by two detectors simultaneously (each looking at a different part of the emission spectrum). The resulting signal ratio (here abbreviated as $S_{\lambda 1}/S_{\lambda 2}$) depends only on the absorption cross-section and the fluorescence quantum yield of the tracer at the respective wavelength ranges[7], as dependencies such as the pulse-to-pulse energy variation and tracer density cancel out, while others such as the efficiency of the detection optics are incorporated in a constant (C).

$$\frac{S_{\lambda 1}}{S_{\lambda 2}} = C \, \frac{\sigma_{abs} \varphi_{f_{\lambda 1}}}{\sigma_{abs} \varphi_{f_{\lambda 2}}} = f\left(T, \upsilon_{o_2}\right) \qquad (2)$$

The fluorescence properties of aromatic tracers such as toluene, naphthalene and anisole have been investigated, calibrated and employed in an engine-relevant planar air-to-fuel ratio as well as thermometry studies [8]. In this study Anisole is selected for air flow, it has good fluorescence spectra at 280nm and 320nm.

PLIF need 266nm wavelength of laser beam so it is preferable to utilize existing laser of 532 nm wavelength used for PIV. For that it is required to convert beam wavelength 532nm to 266nm. Frequency doubling crystal can convert 532nm to 266nm wavelength. Second harmonic generation is a nonlinear optical process, in which photons with the same frequency interacting with a nonlinear material are effectively “combined” to generate new photons with twice the energy, and therefore twice the frequency and half the wavelength of the initial photons. Arrangement of SHG crystal with laser is depicted in Figure 6 under dotted area. KDP crystal is used as a SHG, whenever beam passes through this crystal, it converts into two different wavelengths, so it is required to separate them in order to use 266nm wavelength. To separate 266nm and 532nm beams, dichroic mirror (HBSY0534) is used, the remaining beam with 532nm is dump to beam dump. For imaging, same PIV camera Hisense zyla is used with intensifier (25 mm, multialkali photocathode, P43 phosphor screen). As per equation (2), two images of same flow field are required to generate temperature field. Dual scope fitted with intensifier can capture two images simultaneously using two different filters of 280nm and 320nm. Ratio of images gives intensity of fluorescence which can be converted in to temperature by implementing proper calibration.

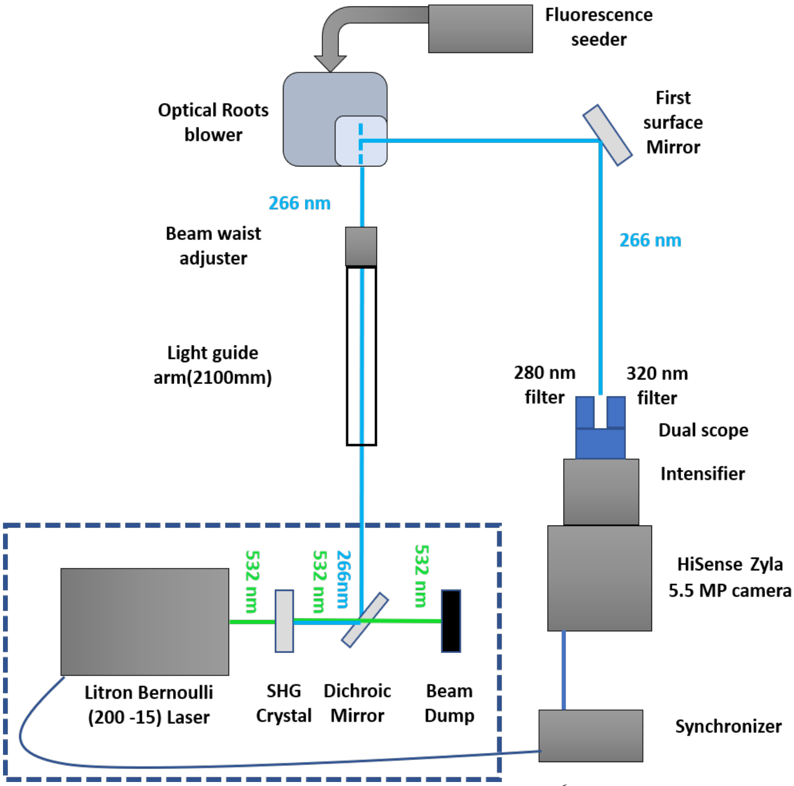

Fig.6. PLIF experiment setup[6]

2.4. High speed infrared thermography

IR thermography has been widely used for surface temperature measurement and it provides an effective approach for non-intrusive and spatio-temporal measurement of temperature. Usually, this technique is applicable for surface temperature measurement. In order to determine temperatures accurately with IR Thermography, careful attention toward a proper choice of windows, elimination of specular reflections from channel walls, and estimation of local emissivity changes are required. The principle of infrared thermography is based on the physical phenomenon that any body of a temperature above absolute zero (-273.15 °C) emits electromagnetic radiation. There is clear correlation between the surface of a body and the intensity and spectral composition of its emitted radiation.[9] By determining its radiation intensity, the temperature of an object can thereby be determined in a non-contact way.

As shown in Figure 7, Infrared thermography setup is relatively simple than the PIV and PLIF setup. ImageIR 8300hp camera has been chosen, it has spectral range of 2 to 5.7 µm,

[6] Image generated by authors

and temperature range of -40 to 1500 °C with full frame rate of 355Hz. Heated air is supplied to take a measurement at various temperature.

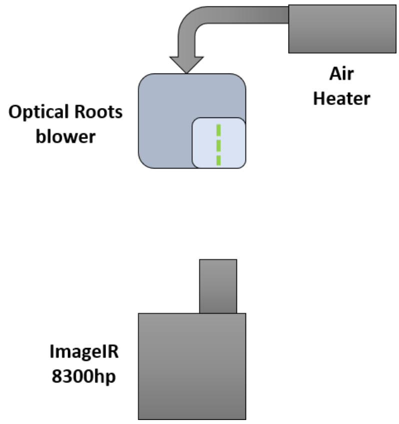

Fig.7. High speed Infrared thermography setup[7]

3. EXPECTED OUTCOME

Developed PIV setup is able to produce velocity field. As per attempt made in past using PIV technique, it can produce velocity field as illustrated in Figure 8[5]. Developed setup is more focused on flow inside the clearance gap.

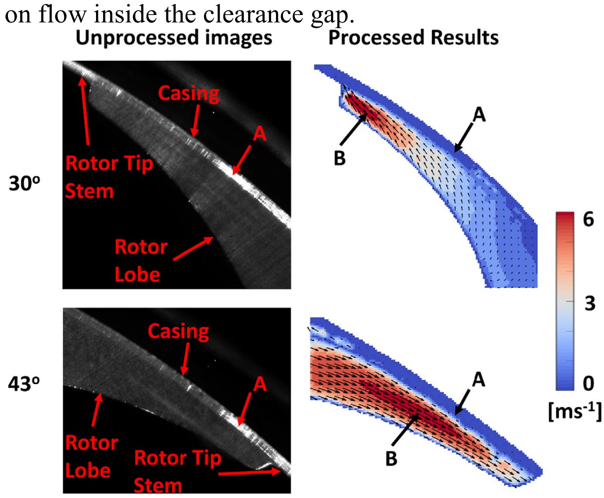

Fig.8. PIV measurement near tip region in roots blower[5]

PLIF setup is developed based on the learning from the feasibility study carried out for PLIF measurement. From the feasibility study, developed setup can produce fluorescence

[7] Image generated by authors

images as Figure 9. Images with pixel intensity (Figure 9 (b)), can be converted into temperature by applying proper calibration process.

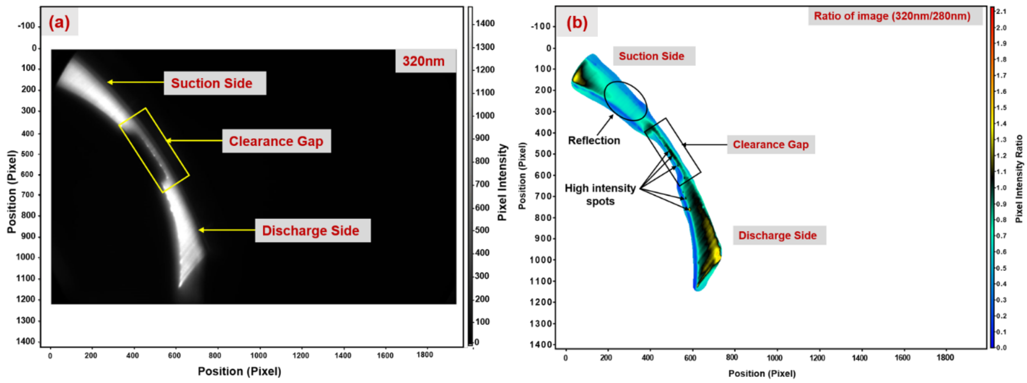

Fig.9. PLIF measurement (a) Unprocessed image (b) Processed image (Image ratio)[8]

Infrared thermography can produce surface temperature measurement. Selected camera can work with 355Hz frame rate, which will be able to take snapshot of lobe surface in running condition and it will allow to produce temperature map as shown in Figure 10.

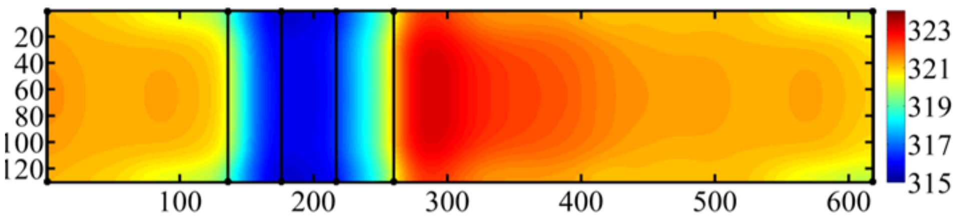

Fig.10. Ribbed Slab Temperature Processing [K] using Infrared thermography[10]

4. CONCLUSION AND FUTURE WORK

This paper presents the experimental program designed to study physics of the operational leakage flows in rotating positive displacement roots blower. Three experiments are developed namely, particle image velocimetry (PIV), laser-induced fluorescence (PLIF) and infrared thermography (IT). PIV setup is equipped with the high speed camera and lenses, which ensures the production of accurate velocity field data. The PLIF setup is an extension of the PIV setup using intensifier, DualScope and fluorescence particles to capture the temperature field within the clearance gaps. The High-speed Infrared Thermography setup is relatively simple because of fewer optical elements involved compared with PIV and PLIF arrangement and can measure lobe surface temperature at frequency up to 355Hz.

[8] Image generated by authors

The results of measurements are being performed at the time of writing this paper. It is expected that they will provide insight in the physics of the leakage gaps at various operating condition of the optical roots blower, and its application will be generalised to other rotary positive displacement machines.

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