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AN INTEGRATED FUZZY-IMAGE PROCESSING APPROACH BASED INFRARED THERMOGRAPHY FOR FAILURE DETECTION AND CLASSIFICATION OF THE STEAM TRAPS

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RESUMEN: La temperatura es uno de los indicadores más comunes para la salud estructural de los equipos y componentes. Hoy en día, la termografía infrarroja (IRT) se utiliza ampliamente como una herramienta de monitorización de la condición utilizando la medición de la temperatura en tiempo real de manera no invasiva y sin contacto para reducir el tiempo de inactividad del sistema, el desastre catastrófico y el coste de mantenimiento. En este trabajo, IRT se utiliza para la inspección de trampas de vapor en los procesos de transporte de vapor mediante la técnica de procesamiento de imágenes y la clasificación de la intensidad de falla en un modelo inteligente. En el modelo inteligente, una cámara de infrarrojos se utiliza inicialmente para capturar la imagen térmica, que se importa como entrada. La detección de fallos se realiza en dos etapas. En la primera etapa, el procesamiento de imágenes proporciona las frecuencias relativas y su relación de modo calculada para tener la entrada adecuada para el modelo difuso como segunda etapa. Los resultados de la primera etapa se importan al modelo difuso para clasificar los fallos de la trampa de vapor. El enfoque de Sugeno basado en el sistema de inferencia difusa (FIS) está diseñado con una estructura simple y números de regla más bajos. El modelo propuesto es simulado por Matlab Software para trampas de vapor sanas y defectuosas. Para demostrar la superioridad también se compara el rendimiento del modelo inteligente propuesto con el software de cámara de termografía por infrarrojos (ULIRvision Model TI160). Los resultados muestran que el modelo propuesto es capaz de condicionar el monitoreo de las trampas de vapor usando IRT sin medir la temperatura, a diferencia de la cámara de termografía infrarroja. Además, el modelo propuesto es capaz de clasificar la intensidad de fallo de las trampas de vapor, a diferencia del software de la cámara de termografía infrarroja, que debe ser evaluada por el experto correspondiente.

Palabras clave: Temperatura, Monitorización de la condición, Termografía infrarroja, Trampa de vapor, Procesamiento de imágenes, Sistema de inferencia difusa

Abstract: Temperature is one of the most common indicators for the structural health of equipment and components. Nowadays, infrared thermography (IRT) is widely used as a condition-monitoring tool using measurement of the temperature in real time in a non-invasive and non-contact manner to reducing system down time, catastrophic breakdown, and maintenance cost. In this paper, IRT is used for inspection of Steam traps in steam transporting processes using image processing technique and classification of failure intensity in an intelligent model. In the intelligent model, an infrared camera is initially used to capture the thermal image, which is imported as input. The failure detection is performed in two stages.

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In the first stage, the image processing provides the relative frequencies and their calculated Mode ratio to have the suitable input for the fuzzy model as second stage. The results from first stage are imported to the fuzzy model to classify the steam trap failures. The fuzzy inference system (FIS) based Sugeno approach is designed with a simple structure and lowest rule numbers. The proposed model is simulated by Matlab Software for healthy and faulty steam traps. In order to show the superiority the performance of the proposed intelligent model is also compared with the infrared thermography camera software (ULIR vision Model TI160). The results show that the proposed model is able to condition monitoring of the Steam traps using IRT without temperature measuring, unlike the infrared thermography camera. In addition, the proposed model is able to classify of failure intensity for the Steam traps, unlike the infrared thermography camera software, which must be evaluated by the relative expert.

Keywords: Temperature, Condition Monitoring, Infrared thermography, Steam trap, Image processing, Fuzzy inference system

1. INTRODUCTION

Condition monitoring as an indicator of the fault development is used to identify the significant changes of the parameters in machinery, which is a major component of predictive maintenance (PdM). The PdM improves the overall equipment effectiveness (OEE), which takes into account the various sub-components of the manufacturing process such as availability, performance, and quality (Bagavathiappan, Lahiri, Saravanan, Philip, & Jayakumar, 2013). Early detection of the imminent equipment failures and preventing them before critical condition, significantly reduce downtime, cost for maintenance, and maximize uptime for the continuous process. In fact, the PdM schedules repairing and rebuilding activities for equipment before the system failure (A. S. Nazmul Huda & Soib Taib, 2013)

Temperature, as one of the most important controlling parameters, is a good way for structure health of the equipment monitoring in various industrial processes. All objects with a temperature above absolute zero emit infrared radiation, which leads to an increase in temperature (Kinch, 2014). Infrared thermography (IRT) is a technique for converting invisible heat into a visual image, which shows the thermal image of the object surface (Bagavathiappan et al., 2013). IRT as condition monitoring technique in a remote, non-contact, and non-invasive way along with identification of the abnormal temperature patterns and measurement of the online temperature assist to early diagnosis of the probable faults to avoid major shutdowns, reduce equipment damage, and maintenance cost. In fact, thermography based diagnosis system allows to the PdM for early prevention of the equipment failure without any interrupting on the running operation, which saves money (A. S. N. Huda & S. Taib, 2013). Due to these advantages, IRT has been established as an effective condition monitoring tool (reader is refereed to for more information about origin and theory of the IRT).(C. Meola, 2012)

For several years, thermography inspection has become an important tool for PdM of surface defect in various materials due to its non-invasiveness, safety, and low cost approach relatively (Brown & Hamilton, 2013) (Paoletti, Ambrosini, Sfarra, & Bisegna, 2013). Therefore, numerous studies are executed to prove thermography as a useful technique in various applications (Dutta, Pal, Mukhopadhyay, & Sen, 2013) (Redaelli et al., 2014).

The IRT is used for various condition monitoring applications such as civil structure monitoring, electrical and electronic components monitoring, deformation monitoring, inspection machines, corrosion monitoring, welding monitoring, circuit monitoring, electronic board monitoring, medicine applications, chemical evaluation process of evaporation monitoring, nuclear applications, and etc. Table 1 shows some recent researches in the IRT based condition monitoring in various applications.

For the piping installation, a stream trap is used to convert a dry steam to liquid water, which is necessary to be in all process. The steam traps are also applied to prevent loss of energy, exit CO2, and separate condensate water from piping for preventing the Water Hammering phenomenon. On the other hand, an infrared thermography can help for these preventions using un-contactless inspection to show inspection result, rapidly ("Infrared Thermography for Temperature Measurement and Non-Destructive Testing," 2014). Therefore, condition monitoring of the steam traps is vital to continuous process in thermography inspection. To the best of authors' knowledge, the steam trap condition monitoring has not yet been considered in the IRT based condition monitoring applications.

Table 1. IRT based condition-monitoring researches in the various applications

Researchers [Ref.]	Year	Subjects
A.S. Nazmul Huda, Soib Taib	2013	Application of infrared thermography for

[2]		predictive/preventive maintenance of thermal defect in electrical equipment
B.B. Lahiri, et al. [14]	2012	Medical applications of infrared thermography:
S. Dutta, et al. [11]	2013	Application of digital image processing in tool condition monitoring:
Wong, Wai-Kit ,et al. [15]	2010	Thermal condition monitoring system using log-polar mapping, quaternion correlation and max-product fuzzy neural network classification
Jadin, Mohd Shawal,Taib, Soib [16]	2012	Recent progress in diagnosing the reliability of electrical equipment by using infrared thermography
Huda, A. S. N. Taib, S. [4]	2013	Suitable features selection for thermal condition monitoring of electrical equipment using infrared thermography
Gowen, A. et al. [17]	2010	Applications of thermal imaging in food quality and safety assessment
Ge, Zhihua, Du, et al. [18]	2011	Performance monitoring of direct air-cooled power generating unit with infrared thermography
Kutin, M., Adamovic, Ž [19]	2010	Tensile features of welded joint testing by thermography
Huda, A. et al. [20]	2014	A new thermographic NDT for condition monitoring of electrical components using ANN with confidence level analysis
Suriani, M. et al. [21]	2012	Detection of Defects in kenaf/Epoxy using Infrared Thermal Imaging Technique
Vincent Leemans Gembloux Agro-Bio Tech, et al. [22]	2011	Evaluation of the Performance of Infrared Thermography for on-Line Condition Monitoring of Rotating Machines
Kafieh, R.,et al. [23]	2011	Automatic detection of defects on polyethylene pipe welding using thermal infrared imaging
Badulescu, C.,et al. [24]	2011	Applying the grid method and infrared thermography to investigate plastic deformation in aluminum multi-crystal
Amon, Francine Pearson, Colin [25]	2010	Thermal Imaging in Firefighting and Thermography Applications
Kumar, et al. [26]	2008	Thermographic studies on IMI-834 titanium alloy during tensile loading
Meola,Carosena [27]	2007	Infrared thermography of masonry structures
Ahmed, et al. [28]	2015	Recursive construction of output-context fuzzy systems for the condition monitoring of electrical hotspots based on infrared thermography
Xu, Changhang Xie, et al. [29]	2014	An infrared thermal image processing framework based on super pixel algorithm to detect cracks on metal surface study

Infrared thermal imaging has now become affordable to wider of specialized physics, technicians, and engineers for increasing its applications. The color of the object surface in the thermal image varies with the surface temperature.(Kylili, Fokaides, Christou, & Kalogirou, 2014) An infrared camera plays an important role in the IRT applications to capture the thermal image and measure of the temperature variations for the object surface (M Vollmer, 2017),(Doubenskaia, Pavlov, Grigoriev, & Smurov, 2013). A special infrared thermal camera takes thermal image in a fixed size from stream trap, while steam trap is under load. To get the thermal image, some specifications such as environment temperature, distance between camera and steam trap, relative humidity, and other specifications according to camera model must be set, firstly and taken the thermal image, secondly. In addition, to detect the failure using thermal camera, the temperature must be measured and analyzed to check the healthy condition of the steam trap by an expert. To cover these problems, an intelligent failure detection model is proposed in this paper.

In the some IRT based failure detections, the intelligent systems are also applied for the prediction and classification of the failure detection for many applications. Some recent works using intelligent systems such as fuzzy, artificial neural fuzzy inference system, and artificial neural network are shown in Table 2. In this paper, a fuzzy inference system (FIS) based Sugeno approach is designed to classify the failure detection of the steam trap status in a linguistic term without any expert as compared with infrared thermography camera software. The designed fuzzy system has simple structure and low rule number as compared with the recent works.

Table 2.The recent used intelligent model for various condition monitoring applications

Researchers [Ref.]	Year	Subjects
Ahmedet al. [28]	2015	Recursive construction of output-context fuzzy systems for the condition monitoring of electrical hotspots based on infrared thermography
Tan, et al. [33]	2007	A novel cognitive interpretation of breast cancer thermography with complementary learning fuzzy neural memory structure
Schaefer, et al. [34]	2009	Thermography based breast cancer analysis using statistical features and fuzzy classification
Wong, Wai-Kit ,et al. [15]	2010	Thermal condition monitoring system using log-polar mapping, quaternion correlation and max-product fuzzy neural network classification
Abdulshahed, Ali , et al. [35]	2015	Thermal error modelling of machine tools based on ANFIS with fuzzy c-means clustering using a thermal imaging camera
Huda, A. et al. [20]	2014	A new thermographic NDT for condition monitoring of electrical components using ANN with confidence level analysis

In this paper, the thermal image, which is taken by thermal camera, is imported in the proposed model as input. The failure detection of the steam trap is performed in two stages using the proposed intelligent model. In the first stage, the image processing provides the relative frequencies and their calculated Mode ratio to have the suitable input for the fuzzy model. The results from first stage are inserted to the FIS based Sugeno model to classify the steam trap failures in the second stage. The proposed model is simulated by Matlab Software for healthy and faulty steam traps. The performance of the intelligent model is also compared with the infrared thermography camera software (ULIRvision Model TI160) in the same conditions

2. DEFECTS IN STEAM TRAPS

All types of steam traps such as mechanical, thermostatic, thermodynamic are destroyed thorough using time. This is due to some reasons like existing CO_2 and high pressure in steam way, which cause steam trap corrosion. This corrosion leads to leakage steam from a transporting pipe to condensate pipe. So, it causes loss of energy and conflicts water and steam, named “Water Hammering”, which makes some defects in steam traps. To overcome the problem, the intelligent model is used for detection the steam trap defects in non-contact way in this paper.

3. THE INTELLIGENT FAILURE DETECTION MODEL

To detect a failure of the steam trap in an easy way or non- contact way, it is important for making a good decision in staying, repairing, or replacing the steam traps. It helps to the maintenance team to the early detection of the imminent equipment failures. The block diagram of the proposed model is shown in Figure. 1. As shown in Figure. 1, the proposed failure detection system is performed in two stages. In the first stage, the image processing provides the relative frequencies and their calculated mode ratio from the thermal thermography camera. The results from first stage are imported to the FIS based Sugeno model to classify the steam trap failures in the second stage. The details of the proposed model are followed in the next sub-sections

3.1 Using image processing technique in thermography image

First of all, in this stage, an ULIRvision Model TI160 as one of the best thermography camera is selected("http://www.ulirvision.com/en/product/thermal-imaging-camera-ti160-3.html. ," 2016). It can be set to analyze the images under the controlled conditions. Thermography image that taken by the camera in special conditions is imported as input in the proposed model. Then, the thermal image is converted from RGB (red green blue) to grayscale of the input image using image processing as the value in grayscale of image shows the temperature (A. S. Nazmul Huda & Soib Taib, 2013). After that, two area first inlet and second outlet of steam trap, which is called region of interest (ROI) is selected. Depend on image size and area, ROI can be resizable. Therefore, it is important to have same size for both ROI from inlet and outlet of steam trap. In the next step, the

ROI areas are cropped to calculate the related frequency for each ROI. The relative frequency is intensity value of each pixel to total intensity valve (equal to 256) of image. Besides, the ROI modes are calculated from their relative frequency, separately. The mode is maximum value of the grayscale image value as compared to other grayscale value of the image. Calculated modes lead to obtain two number, which is used for comparing inlet and outlet ROIs in a fuzzy model. Finally, the calculated ratio of the modes is inserted in a fuzzy model to classify the failure intensity.

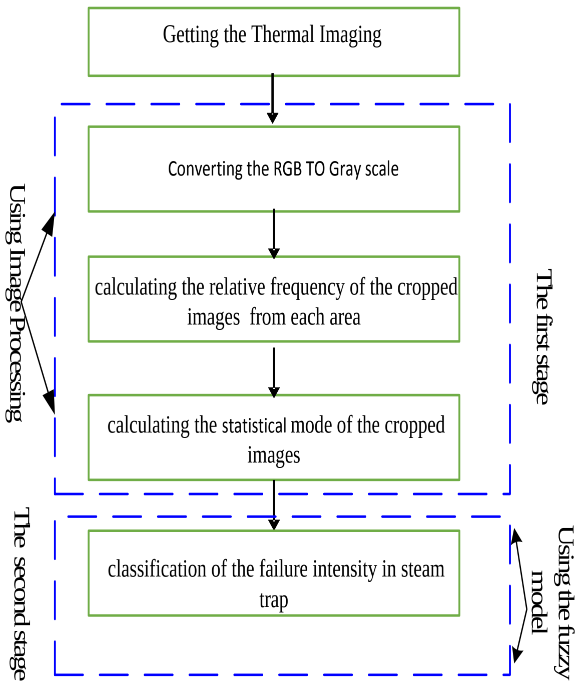


Figure. 1. The intelligent failure detection model.

3.2. FUZZY MODEL

Zadeh (1965) introduced fuzzy set theory to cope with the uncertainty (L. A. ZADEH Department of Electrical Engineering and Electronics Research Laboratory & University of California, 1965), which is inherent to the human judgments in decision making processes through the use of linguistic terms and degrees of membership (Amindoust, Ahmed, Saghafinia, & Bahreininejad, 2012). A fuzzy set is a class of objects with grades of membership. A normalized membership function is between zero and one. The most common approaches to fuzzy inference system (FIS) are Sugeno and Mamdani approaches. In this paper, a Sugeno approach is used because of the fuzzy output changes is linearity (M Van Pelt - Seattle).

The FIS based Suegno approach is designed with one input and one output variables with the possibility of the input changing in a certain range [0 256]. It is noted that the ratio of the modes is inserted as input fuzzy, which changes in a certain range [0 1]. Moreover, the input membership functions (MFs) are applied in the trapezoidal and triangular forms in this paper. The input MFs are calculated from the Mode, which are shown in Figure. 2. The input MFs in the form of linguistic variables include "Low," "median," and "High" as shown in Figure. 2. The out variables are considered as fixed values so that their changes is linearity and in the form of linguistic variables are "severe leakage", "Low Leakage", and "Good". The rules are determined based on comparing inlet and outlet ROI to make a good decision for steam trap condition monitoring as shown in Table 3. A set of the fuzzy linguistic rules based on expert knowledge are utilized to implement our fuzzy decision model.

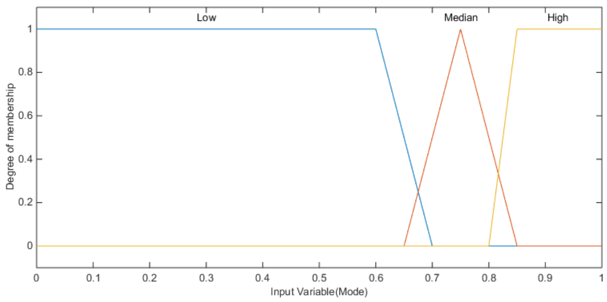


Figure. 2. The input membership function.

Table 3.Fuzzy rule based matrix for the FIS based Sugeno approach

		Fuzzy output
Fuzz y	Low	Good
	Median	Small Leakage
	High	Severe Leakage

To determine the range of input variables and classify the failure intensity some points are considered based on the characteristics of the steam traps (Yang, 2013) as follow.

•The supplied pressure is 25,000 pounds, which is equal to 10 bar. Based on the temperature-pressure thermodynamic tables, the available temperature in the system is 170 ° C. This pressure is reduced to 3.5 bar for using in the steam traps so that the temperature is reduced to 140 ° C.

•Due to condensate performance, when the steam entries to steam trap, the pressure decreases and the steam temperature reach to 100 ° C. If the steam temperature in the outlet of the steam trap gets less than 100 ° C, the leakage of the steam is equal to zero and it works properly.

•Since the grayscale image intensity of the ROI from the steam trap directly shows the temperature, the temperature ratio of the outlet 100 ° C to inlet 140 ° C can be considered as the corrupt border of the steam trap and used for the steam traps status.

Based on the aforementioned issues and consideration a temperature range of 20° C, the failure classification can be taken into account as follows. This classification is shown in Table 4.

1. If the steam temperature in the steam trap inlet is 140 ° C and outlet temperature is 100° C, the ratio of input to output temperature is 0.7 and steam trap is considered as healthy steam trap or "Good."
2. If steam temperature in steam trap inlet is 140° C and outlet temperature is 120° C, the ratio of input to output temperature is 0.85 and steam trap is placed in a poor conditions or "low Leakage."
3. If steam temperature in steam trap inlet is 140° C and outlet temperature greater than 120 ° C, steam trap is placed in a severe conditions or "severe Leakage".

Table 4.The classification failure for the steam trap status

Degree	Intensity value	status	Maintenance action
1	Mode(outlet) ≥ 0.85 Mode (inlet)	severe Leakage	Change the steam trap
2	0.7 Mode (inlet) ≤Mode(outlet) < 0.85 Mode (inlet)	low Leakage	Insert in planning for maintenance
3	Mode(outlet) < 0.7 Mode (inlet)	Good	Steam trap is oky

4. RESULT AND DISCUSSION

The proposed intelligent model is simulated using MATLAB programming. In the proposed model, thermal image that taken by thermal camera (ULIRvision Model TI160) in the suitable situations is imported in the MATLAB script file (m. file) as an input. The proposed model is simulated for the healthy and faulty steam traps step by step as described in the Section 4.1. Then, the calculated Modes are imported in the fuzzy model to classify the steam trap failures.

The results are extracted from the camera software for the healthy and faulty steam traps in the same conditions with the intelligent model. To show the effectiveness of the proposed model, these results are compared with the output results from the intelligent model. The results will be presented according to Section 4.1, 4.2 and discussed in the next sub-sections.

4.1. The simulated results of the proposed model for the steam trap under healthy condition

The thermal image that taken by thermal camera is shown in Figure. 3 (a). The grayscale of the input Figure is shown in Figure 3(b). The selected ROI in steam inlet and outlet ways of steam trap are shown in Figures. 3(c) and (f), respectively by running an image processing function on MATLAB. As mentioned in the Section 4.1, the selected area must be fixed to have same size for both inlet and outlet areas, which are shown in Figure. 3(d) and (g). The relative frequencies of the cropped and fixed inlet and outlet areas are shown in Figure. 3(e) and (h), respectively by inserting them in to MATLAB mathematic function, which calculates the relative frequencies. Finally, the Mode values for ROI in the input and output of steam trap are obtained equal to 230 and 135, respectively. In this stage, the fuzzy model, which written by MATLAB is executed. Finally, the fuzzy model output shows the steam trap status is healthy. The ratio of the Mode values is obtained equal to 0.587(135/230). Based on the Table 3, this value is less than 0.7, which shows the result of the fuzzy model output is true.

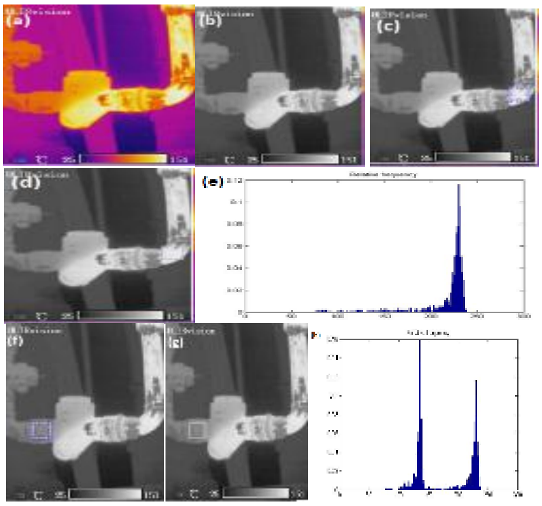


Figure. 3. The simulated results of the proposed model for the steam trap under healthy conditions; (a) the input thermal image from camera, (b) the grayscale image from input image, (c) the selected ROI in steam inlet way of steam trap, (d) the cropped and fixed inlet area, (e) the relative frequency of the cropped and fixed inlet area, (f) the selected ROI in steam outlet way of steam trap, (g) the cropped and fixed outlet area, and (h) the relative frequency of the cropped and fixed outlet area.

4.2. The simulated results of the proposed model for the steam trap under faulty condition

For the faulty condition, the same procedure as mentioned in Section 5.1 is done. The simulated results for the steam trap under faulty condition are shown in Figure. 4(a)-(h). The Mode values for ROI in the input and output of steam trap are obtained equal to 222 and

222, respectively. The fuzzy model output shows the steam trap status is faulty. The ratio of the Mode values is obtained equal to 1.00(222/222). Based on the Table 3, this value is more than 0.85, which shows the result of the fuzzy model output in this condition is also true.

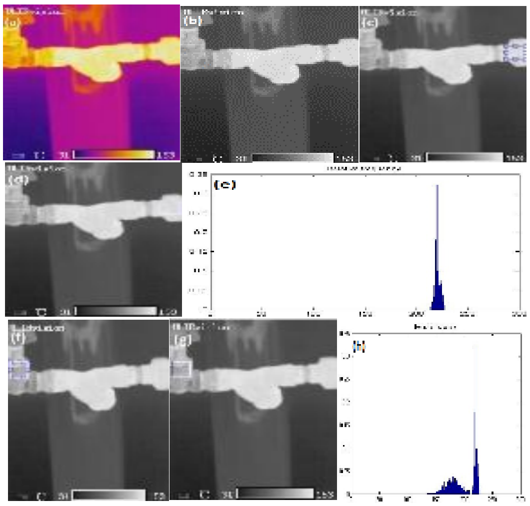


Figure. 4. The simulated results of the proposed model for the steam trap under faulty conditions; (a) the input thermal image from camera, (b) the grayscale image from input image, (c) the selected ROI in steam inlet way of steam trap, (d) the cropped and fixed inlet area, (e) the relative frequency of the cropped and fixed inlet area, (f) the selected ROI in steam outlet way of steam trap, (g) the cropped and fixed outlet area, and (h) the relative frequency of the cropped and fixed outlet area.

4.3. Validation the proposed intelligent model

To validate the proposed model, the performance of the proposed model is compared with the output results obtained from the camera software (ULIRvision Model TI160) with the same operation condition for the steam trap failures.

The thermal image that taken by the camera are shown in Figure. 5. As shown in Figure. 5, the thermal analyzing is performed using the camera software. The results from the camera outputs will be shown and discussed for healthy and faulty steam traps in next sub- sections.

4.3.1 The extracted result of the camera software for the steam trap under healthy condition

The extracted result for the steam trap under healthy condition is shown in Figure. 6. As shown in Figure. 6, the input parameters are adjusted by the operator before taking the thermal image. Moreover, the camera needs to measure the temperature to the give the validation result as the temperature is measured in the two places (P0, P1) as shown in Figure. 6. Based on the measured temperature, software shows the healthy condition for the steam trap, which must be evaluated by the relative expert.

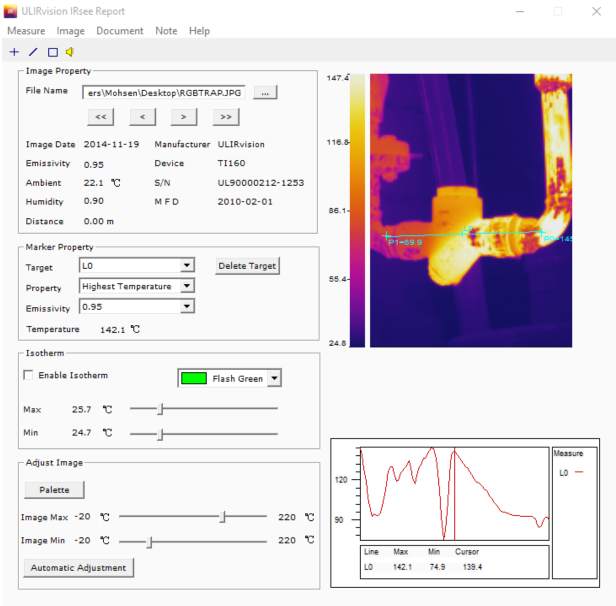
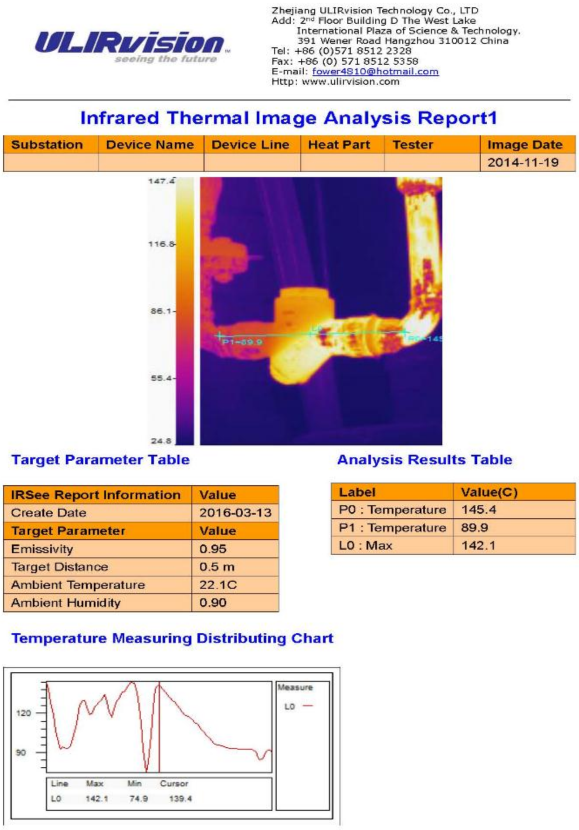


Figure. 5. The input thermal image of the camera software for the steam trap.



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Infrared Thermal Image Analysis Report1

Substation	Device Name	Device Line	Heat Part	Tester	Image Date
					2014-11-19

Target Parameter Table

IRSee Report Information	Value
Create Date	2016-03-13
Target Parameter	**Value**
Emissivity	0.95
Target Distance	0.5 m
Ambient Temperature	22.1C
Ambient Humidity	0.90

Analysis Results Table

Label	Value(C)
P0 : Temperature	145.4
P1 : Temperature	89.9
L0 : Max	142.1

Temperature Measuring Distributing Chart

Figure. 6. The extracted result of the camera software for the steam trap under healthy condition

4.3.2 The extracted result of the camera software for the steam trap under faulty condition

The extracted result for the steam trap under faulty condition is shown in Figure. 7. Like previous sub-section, the operator adjusts the input parameters before taking the thermal image as shown in Fig. 7. The temperature is also measured in the two places (P0, P1) as shown in Figure. 7. Based on the measured temperature, software shows the faulty condition for the steam trap, which, must be evaluated by the relative expert.

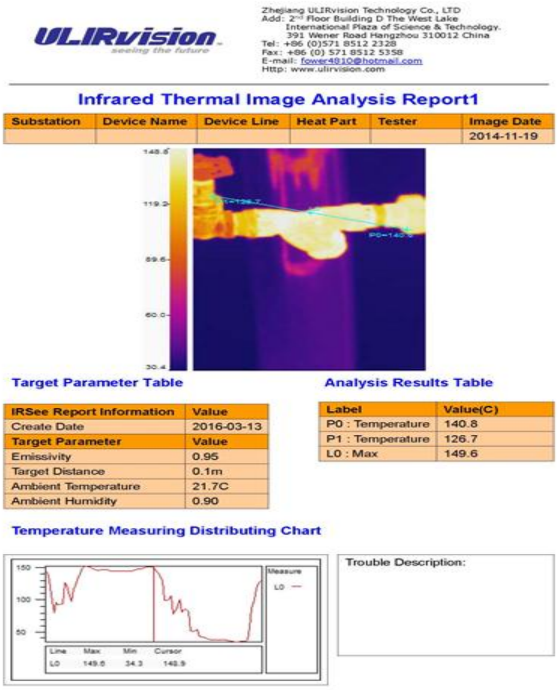

Figure. 7. The extracted result of the camera software for the steam trap under faulty conditions.

The results in the Section show that the proposed intelligent model is able to condition monitoring of the Steam traps using IRT without measuring of the temperature, unlike the camera software. Moreover, the proposed intelligent model is able to classify of failure intensity for the Steam traps, unlike the infrared thermography camera software, which must be evaluated by the relative expert.

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