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Thermal Monitoring for Condition Based Maintenance of an X-ray Generator

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Summary

- Outer surface temperature profile of the X-ray generator was obtained with Infrared (IR) sensors
- Infrared sensors measurements were verified with data from installed contact thermometers.
- Only two contact sensors are sufficient to estimate the technical condition of the X-ray generator
- Measurements can be made by infrared cameras (IR sensors) only on visible areas, or with contact sensors where not
- Oil flow patterns inside the X-ray generator cause the highest temperature measurements at the unit edges

Objectives

Reliable measurement of surface temperature and estimation of the possible highest temperature inside of X-ray generator made by Smiths Heimann Gmbh of HS 100100V type.

Introduction

The modern Non-Intrusive Inspection Systems (NIIS) are complicated machines that rely on X-ray generator and provide detection capabilities, supported by state-of-the-art electronics, electro-mechanics, software algorithms and solutions. They are the backbone of air transportation security. Currently the commercial aviation is impossible without NIIS. Thus, the adequate real-time evaluation of the NIIS technical condition is critical for a smooth airport operation. However, most of the NIIS operating worldwide are designed before the Internet of Things (IIoT) era, and they don't have the capabilities to provide information in real-time about their technical status.

A solution for condition-based and predictive maintenance, developed recently (Predictive Maintenance Tool for NIIS – PMT4NIIS), aims to provide an early warning for possible failures based on predictive algorithms using machine learning and AI technologies [1]. That solution relies strongly on the technical data collected from the NIIS itself, along with retrofitted sensors designed to monitor different physical and environmental parameters [2].

Approach

In the present study, we propose a 2D thermal monitoring approach as a new source of valuable data for estimating the x-ray generator's technical condition and input to the predictive models. The study provides both semi-analytical and experimental results. The proposed semi-analytical model has been compared with the experimental results based on the large datasets (big-data), collected by the sensors. The experimental setup consists of contact sensor arrays combined with a distant infrared sensors system, to provide the temperature mapping of the entire outer surface of the x-ray generator. This data is used for the thermal model boundary conditions. The examined x-ray generator is the most common type, equipped with a stationary anode x-ray tube, mounted on an HS 100100V (Smiths Heimann Gmbh). This x-ray generator type is widely implemented on similar x-ray security inspection systems for luggage and cargo. The thermal parameters of the x-ray generator were studied during numerous long tests run series conducted on HS 100100V, located at the Danlex research center. To reach a steady state of the x-ray generator thermal parameters, most of the respective test runs have lasted more than 24 hours of continuous workload (x-ray beaming), simulating real- world operating conditions.

Installation of IR Sensors:

Mounting of four IR sensors MLX90640 – BAB (-40 ÷ +200 °C) 32 x 24 px matrix was performed according to their technical specification (denoted S33÷S36), accuracy ±2.0°C

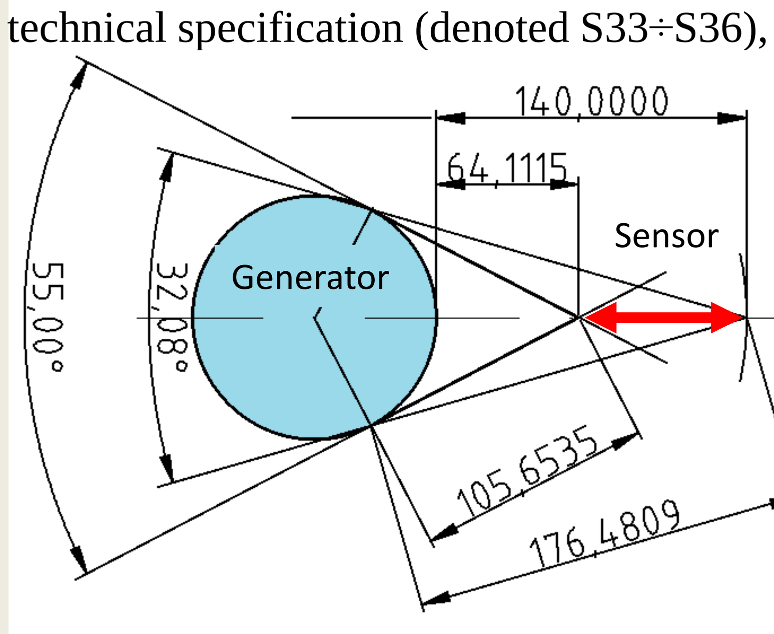
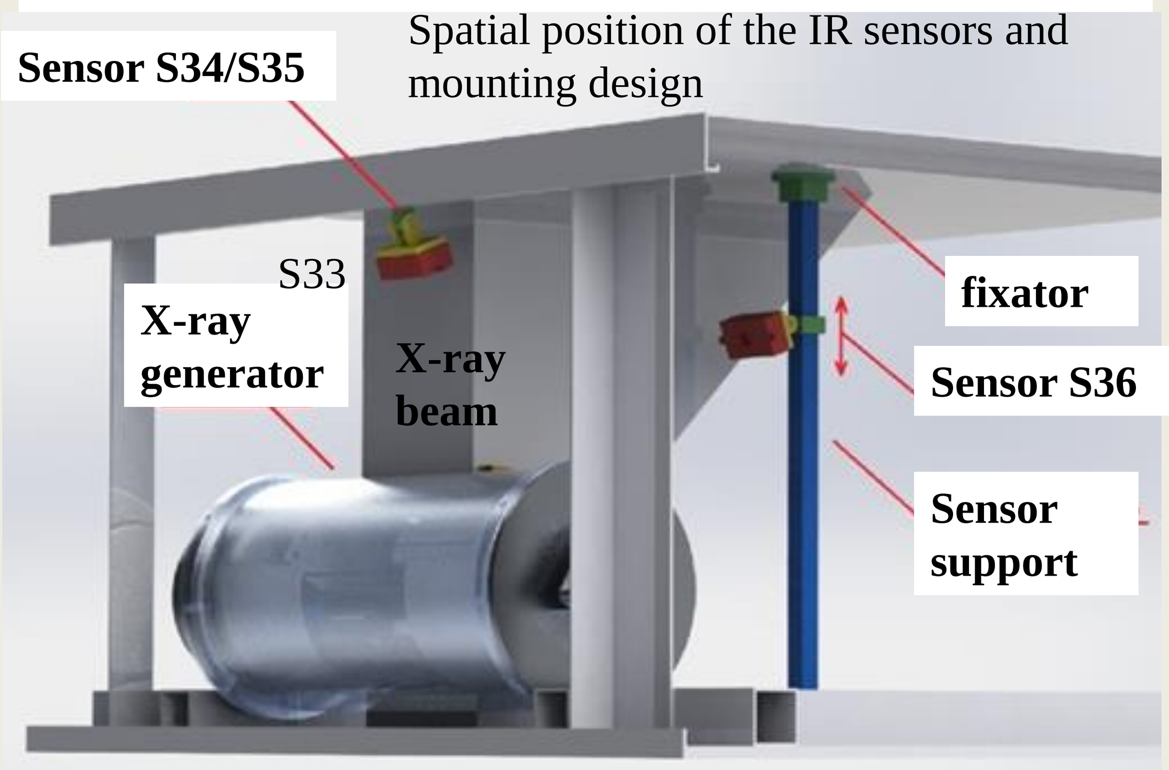


Image detection angle range of 55° ÷ 32° is used to define optimal distance along the optical axis

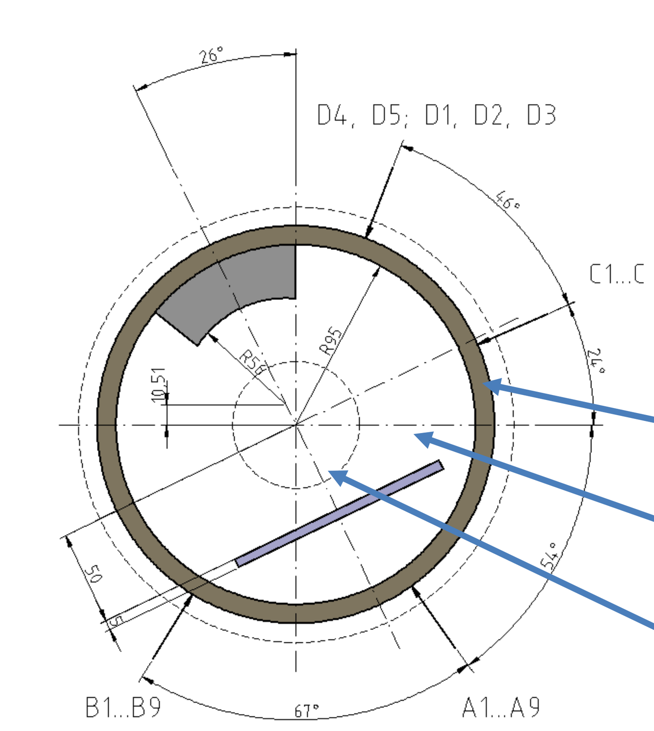
Sensor S34/S35

Spatial position of the IR sensors and mounting design



S33 and S35 placed symmetrically regarding X-ray beam

Mounting of Contact Thermometers:



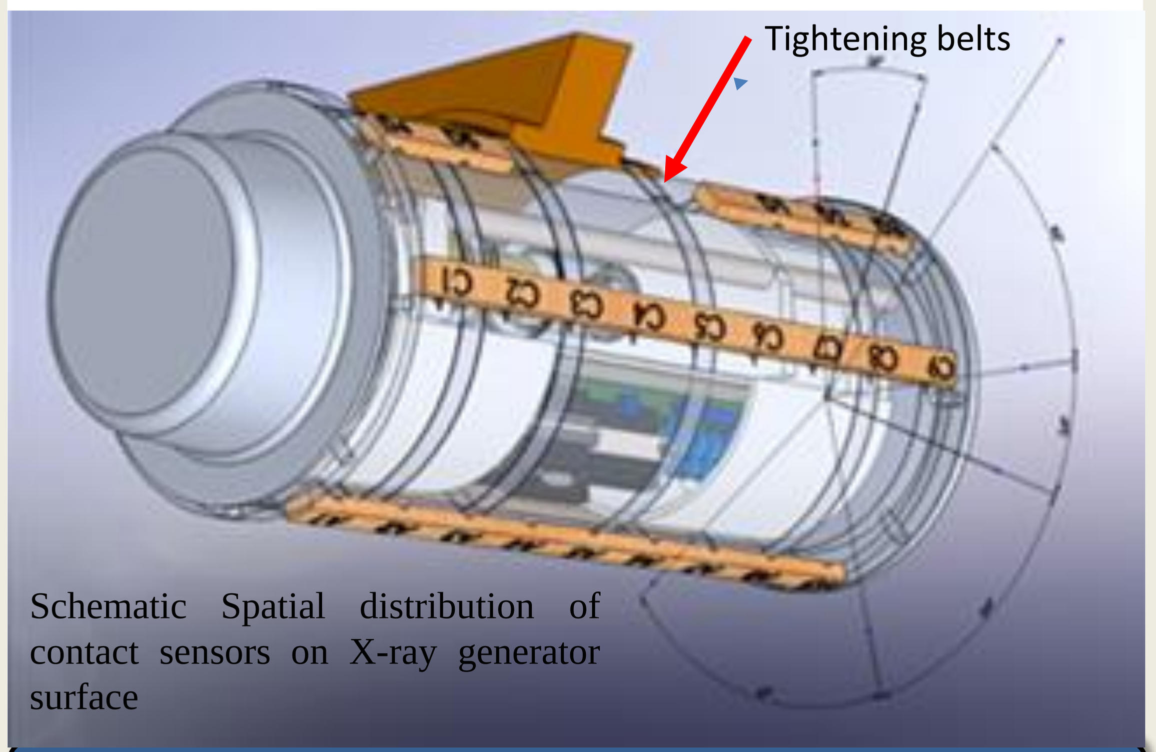
Installed 35 digital contact temperature sensors, DS18B20 (-55°C to +125°C with accuracy ±0.5°C) on 4 lines (denoted with a Latin letter) mounted on the generator surface.

X-ray generator outer wall

Generator oil volume

X-ray beam generation tube

Coordinates of sensors mapping on the X-ray generator surface

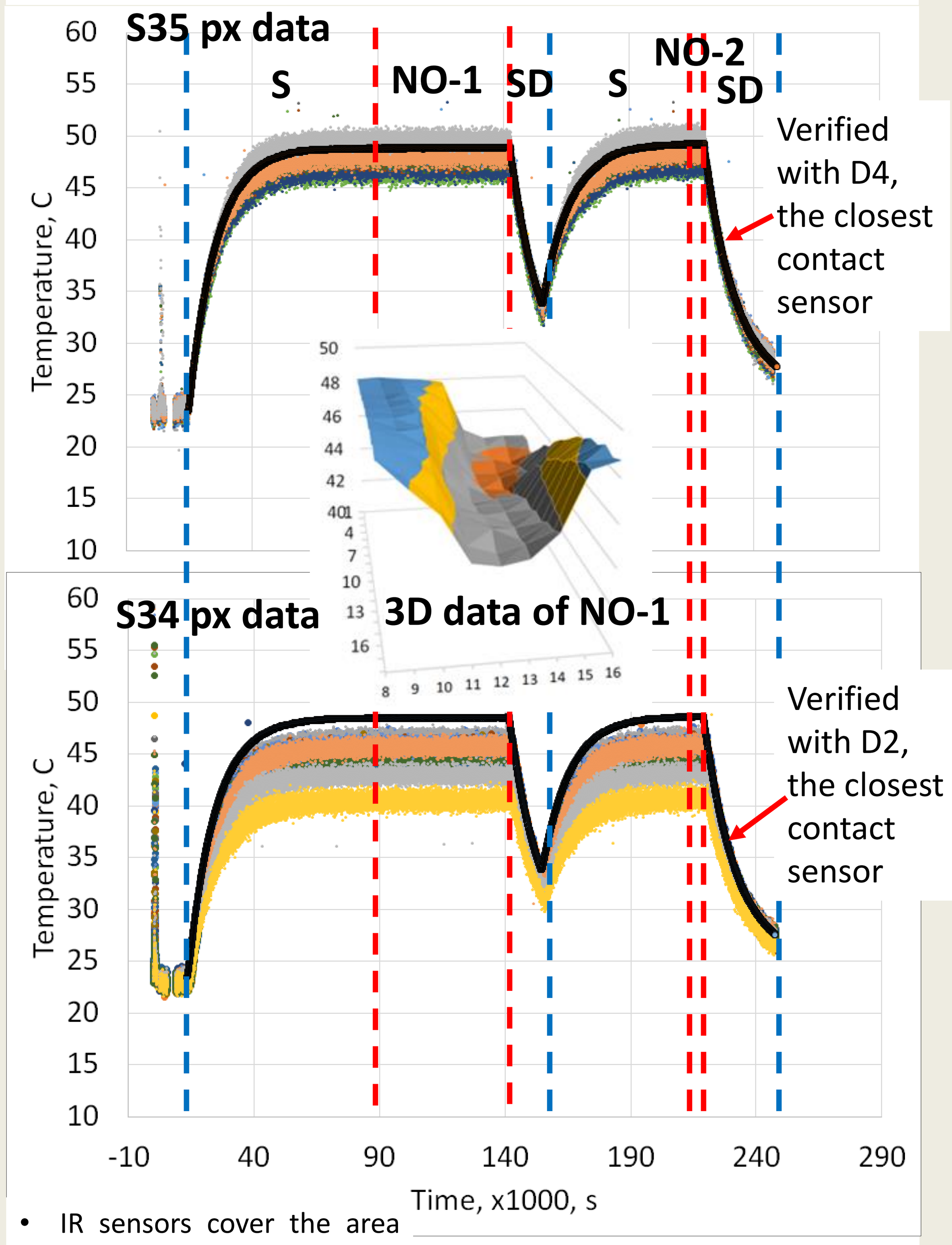


Schematic Spatial distribution of contact sensors on X-ray generator surface

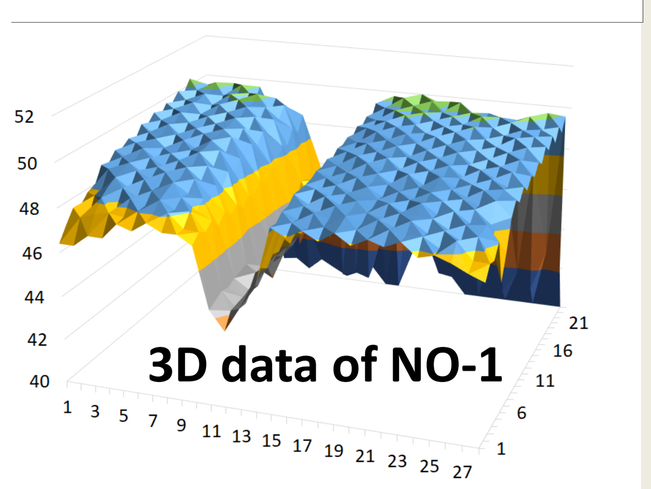
Selection of Data for Analysis

Potential modes of interest: regimes in which the operation of the X-ray generators is independent of time (stationary regimes). The most important of them is the operation of the equipment in a continuous scanning mode that is the normal operation of HS 100100V type machines. During the operation of any machine, the following three modes can be differentiated: Starting (S), normal operation (NO) and shut-down (SD). Task set is to study the stationary regimes of NO because they are important for future analysis of reliability and predictive maintenance implementation.

All IR sensors were mounted at 140 mm from generator surface to avoid data from pixels at the FOV edges, because of the lower accuracy ±3.0C. With special calibration sets we found that distance between two pixels is v:h = 8:6 mm in average. From S33 and S36 we could not obtain reliable data and found that only results from S34 and S35 are sufficient.

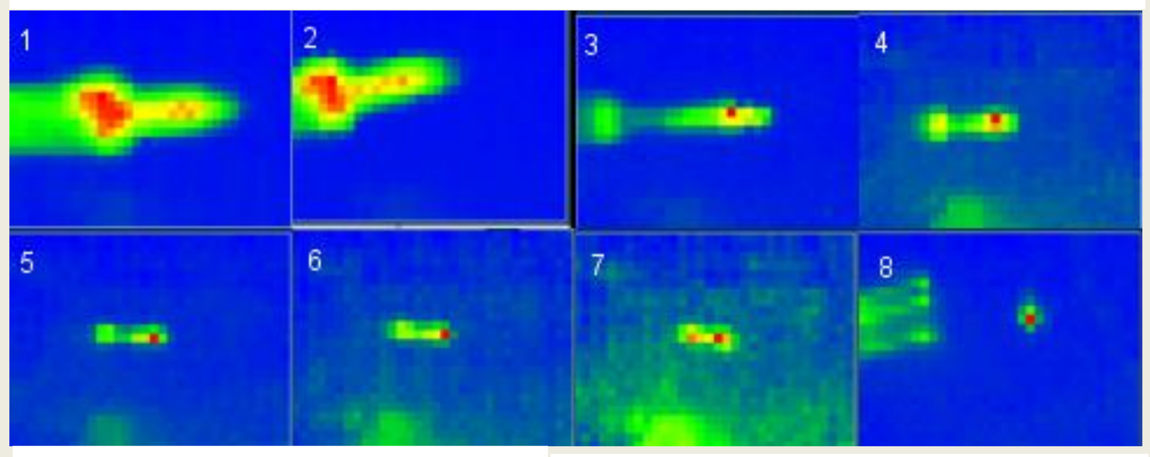


- IR sensors cover the area with highest surface temperature. A temperature minimum is observed at the metal X-ray beam channel that provide acts as a heat sink.
- Some surface zones are blocked by generator fixtures and cannot be observed directly

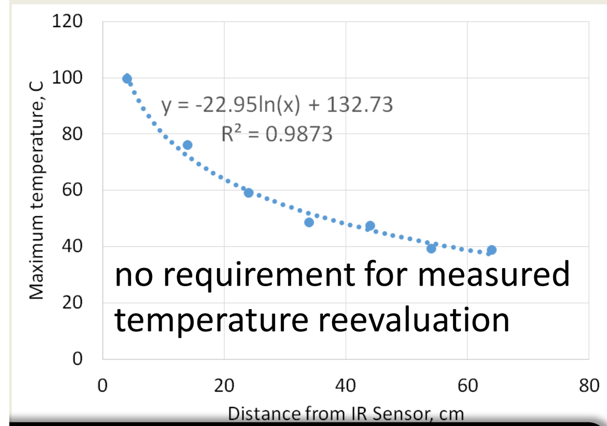


Estimation of IR Sensors Resolution

The assessment of the resolution of the IR sensors was carried out as follows: In laboratory conditions, a hot-tip solder was placed in front of the camera at various fixed distances. A sequence of images is used to determine the spatial sensitivity of the IR sensors. The results show in a decrease in the resolution of the cameras with an increase in distance.



- At a distance greater than 20 cm, the image resolution is greater than the tip leading to the background temperature masking foreground objects.
- The effect follows logarithmic law.
- The optimal measurement distance is about 14 cm from the measurement source to minimize the number of sensors



Analytical Results

Two characteristics can be indicators for operational conditions of X-ray generator: surface temperature and oil density. Surface temperature is used for evaluation of internal temperature near X-ray tube.

The applied equation: $\frac{1}{r}\frac{d}{dr}r\lambda(r,\varphi)\frac{dT}{dr} = 0$

Boundary conditions

Outer wall: $-\lambda_w \frac{\partial T}{\partial r}\Big|_{r_w-\delta} = a_{air}(T_o - \overline{T_{airb}}) = a_{air}[f(s) - \overline{T_{airb}}]$

and $T_{air}|_{r_o+\delta} = T_{out}|_{r_{out}-\delta} = f(s)$ where $f(s)$ outer wall temperature profile

Inner wall: $-\lambda_w \frac{\partial T}{\partial r}\Big|_{r_w+\delta} = -\lambda_o \frac{\partial T}{\partial r}\Big|_{r_w-\delta}$ and $T_o|_{r_w-\delta} = T_w|_{r_w+\delta}$

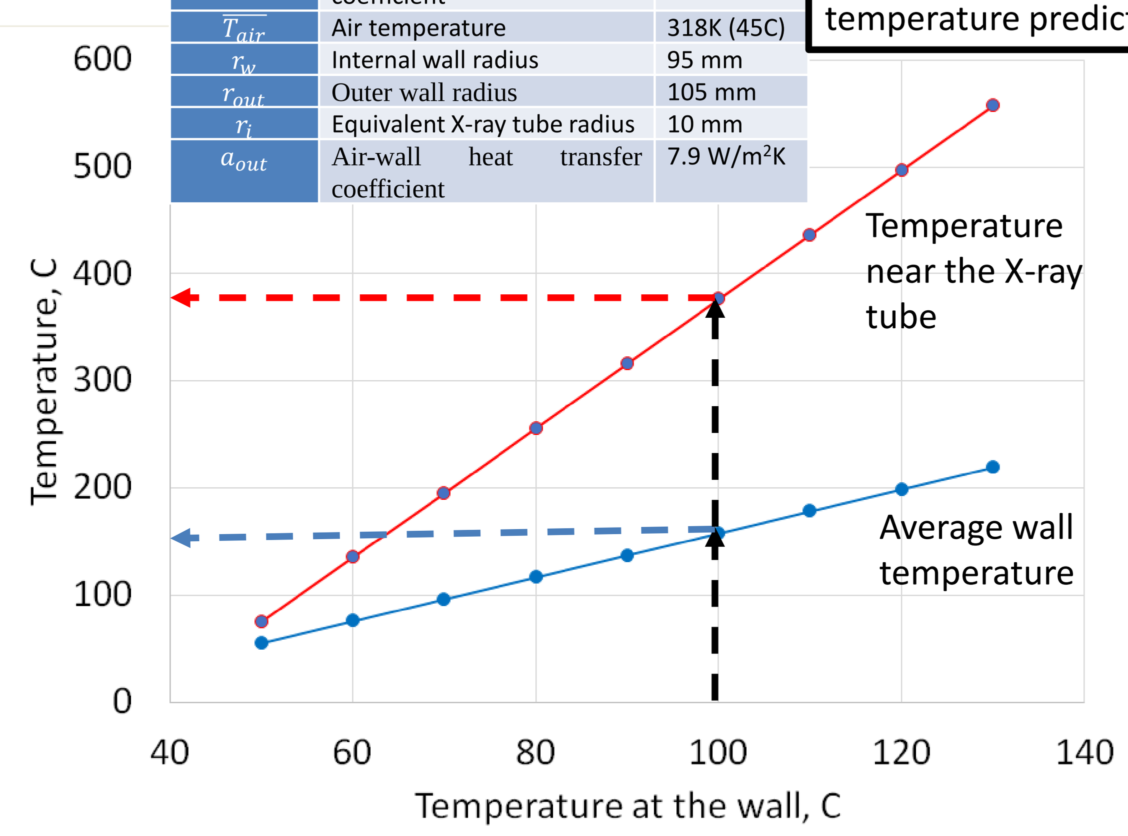
The analytical solution

solid wall: $T = \left\{-\frac{r_{out}}{\lambda_w}[a_{out}(f(s) - \overline{T_{air}})]\right\}\ln r + f(s) + \frac{r_{out}\ln r_{out}}{\lambda_w}[a_{out}(f(s) - \overline{T_{air}})]$

oil volume: $T = \left\{-\frac{r_{out}}{\lambda_o}[a_{out}(f(s) - \overline{T_{air}})]\right\}\ln r - \left[\left(\frac{1}{\lambda_w} - \frac{1}{\lambda_o}\right) r_{out}\ln r_w - \frac{r_{out}\ln r_{out}}{\lambda_w}\right]\left\{\frac{r_{out}}{\lambda_w}[a_{out}(f(s) - \overline{T_{air}})]\right\} + f(s)$

Parameter	Description	Value
λ_o	Oil heat transfer coefficient	0.3714 W/m.K
λ_w	Wall heat transfer coefficient	52 W/m.K
$\overline{T_{air}}$	Air temperature	318K (45C)
r_w	Internal wall radius	95 mm
r_{out}	Outer wall radius	105 mm
r_i	Equivalent X-ray tube radius	10 mm
a_{out}	Air-wall heat transfer coefficient	7.9 W/m²K

Analytical solution allows development of simplified model for temperature prediction



The second factor predicting the condition of the machine is the expansion of the oil. Data obtained from [3] shall be used for this purpose. When applying the formula: $\Delta V = V_0\beta\Delta T$, V_0 is the initial volume (at 20°C), β is the compressibility of the oil, defined by β = 5×10^{-07}T + 0.0007 for a given temperature T, K, ΔT is the temperature difference. It is known that the expansion cuff of the X-ray generator absorbs normally about 300–500 ml oil, which is within normal operation up to about 60°C at the outer wall. A maximum permissible limit of 80 °C will occur earlier than the temperature damage to the X-ray tube.

References:

1. Georgi Nalbantov, Dimitar Todorov, Nikolay Zografov, Stefan Georgiev, Nadia Bojilova. Predictive Maintenance Tool for Non-Intrusive Inspection Systems. https://arxiv.org/abs/2103.01044 1 Mar 2021.
2. Nikolay Zografov, Danlex EOOD. EP3955707 - METHOD AND SYSTEM FOR PREDICTING A FAILURE PROBABILITY OF A COMPONENT OF AN X-RAY SYSTEM https://register.epo.org/application?number=EP20190781 https://data.epo.org/publication-server/document?iDocId=6754017
3. Е. И. Казанцев, Промышленные печи, Москва: Металлургия, 1975

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