Development of XR75 X-ray Inspection System

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[Summary] We have developed a new long-life, cooler-less X-ray inspection system. To extend the life of key parts, we developed a new X-ray sensor with much greater sensitivity than previous sensors. This new sensor enabled us to reduce the output of the X-ray generator, extending the life of the X-ray tube by threefold compared to previous systems. In addition, the lower output of the X-ray generator greatly reduced heat generation, facilitating a new cooler-less design.

1 Introduction

X-ray inspection systems have been used by the food processing industry for more than 20 years. During this time, the range of inspected foodstuffs has grown from primary products, such as meat, fish, and agricultural products, to processed foods, such as sweets, frozen foods, noodles, etc. With the increasing range of target foods, the variety of shapes, food thickness and width as well as the materials, have required to revise configuration and performance as well support for changing validation standards. As one example, machines with several conveyor belt widths have been introduced to food processing lines to cope with the size of inspected foods along with abiding food industries' new requirements, striving to put in consideration 100 keV X-ray generator that has sufficient penetration rate for inspected-products like 100 mm thick cheese. At this type of first-stage development, the actual products to be inspected are confirmed, and the focus is on perfecting the product line-ups to support those inspected foods.[1) to 4)]

However, after customers have actually installed inspection systems in their production lines, the emphasis is on how to cut running costs by developing cooling systems with low running costs to help lengthen the life of core components, particularly X-ray generator and X-ray sensor, reducing the need of replacing these expensive and short-lived parts. To meet this need, Anritsu has spent many years improving the key functions of its inspection system products and has successfully developed new technologies to solve these issues. These technologies are incorporated into Anritsu X-ray inspections systems and low-output X-ray inspection systems with excellent detection sensitivity. Technology advances to extend the life of the X-ray generator have included suppression of damage to the X-ray tube by reducing the X-ray generator output with better quality of cooling oil. At the same time, reducing the X-ray output also suppresses deterioration on the X-ray sensor, helping extend its life as well. Furthermore, since reducing the power consumption of the X-ray generator with less heat generation and added some contraption to thermal design it made us to succeed for eliminating cooling equipment. This article outlines this upgrade and explains its contents and merits.

Figure 1 Exterior of X-ray Inspection System

2 X-ray Inspection System

The X-ray inspection system is consist with an X-ray generator, X-ray sensor, and conveyor belts. The inspected products are carried by the conveyor belts through the X-ray beam to create a transmission image that is to be image–processed. The newly developed X-ray inspection system has the same basic structure and functions as previous Anritsu designs. This section introduces the operation principles and also explains the factors influencing the life of the X-ray generator and X-ray sensor.

2.1 Operation Principle

Figure 2 shows the basic structure of the inline-type X-ray inspection system composed of an X-ray generator, a linear sensor-type X-ray sensor, and conveying systems such as belt conveyors. The beam of X-rays generated and output from the X-ray tube irradiates a section of the belt conveyor. The X-ray sensor under the conveyor receives the beam. Products to be inspected are carried by the belt conveyor through the X-ray beam over the X-ray sensor to be taken continuous imaging. The X-ray inspection system uses an image processing algorithm to process the transmitted image of the inspected product and detect (at high sensitivity) any foreign objects in it.

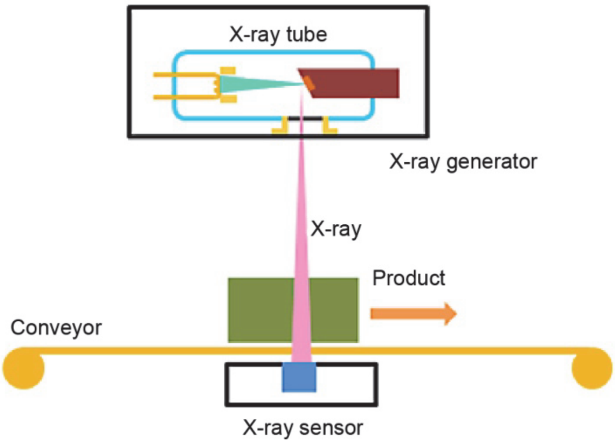


Figure 2 Structure of X-ray Inspection System

2.2 X-ray Tube Life

Figure 3 shows the basic structure of the X-ray tube used in this system. X-ray tube is composed of a filament, Wehnelt, target, anode, beryllium window and flange. These parts are mounted in a glass container evacuated to high vacuum of 10^{-6} Pa. The filament is heated to maintain a condition radiating thermions (thermal electrons) and a high voltage of 20 to 30 kV is impressed between the filament and the target. Thermions flying off the filament strike the target with high kinetic energy to generate braking X-rays. Mounting the target at an oblique angle of 90° reflects the generated X-ray through the beryllium window to irradiate the required location.

The life of the X-ray tube is determined by two factors: 1. The burn-out of the filament, and 2. Loosing the degree of vacuum in the X-ray tube. Filament life has been improved over many years by various measures and today life has been greatly extended by including tungsten in the main filament materials. On the other hand, loosing the degree of the vacuum is caused by outgassing of the materials in the X-ray tube into the vacuum. Although as much gas in the materials is removed as possible at manufacturing process, there are limits to the processing and not all gas can be perfectly removed. This outgassing occurs while the X-ray tube is in use, and gases are generated from secondary materials surrounding areas struck by thermions from the filament. Increasing the X-ray tube output results in more outgassing; in previous X-ray tubes, lowering the output reduced the outgassing and the problem of loosing the vacuum help extending the X-ray tube life. Consequently, using low-output rather than high-output tubes is a key point in extending the life of X-ray tubes.

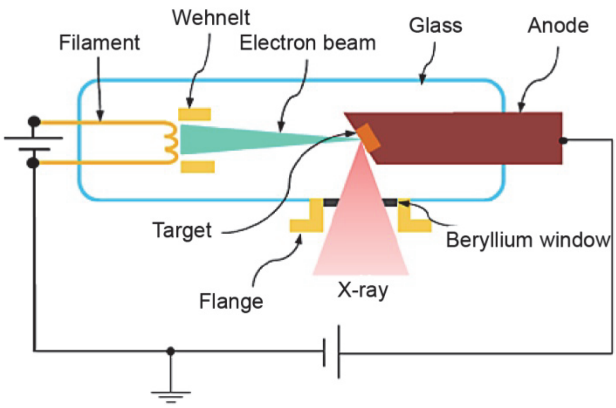


Figure 3 X-ray Tube Structure

2.3 X-ray Sensor Life

As shown in Figure 4, the X-ray sensor is composed of a scintillator, photodiode, and reading circuit. The X-ray detection principle is described below.

First, the generated X-rays reach the scintillator which converts them to visible light detected by the photodiode. The photodiode converts the visible light to an electrical charge that is passed to the connected reading circuit which has a capacitor where stores the charge and trigger switch passing this charge to external. The charge is captured by controlling this trigger switch. Measuring the size of this charge can determine the power of the transmitted X-rays.

Two factors cause differences in the life of the X-ray sensor are: 1. Scintillator aging, and 2. Photodiode aging. The former causes decreasing the conversion rate of X-ray to visible light. On the other hand, the latter causes a decreasing in the scintillator sensitivity to converted light from X-rays. Combining those aging effects both scintillator and photodiode in the X-ray sensor degrades the overall detection performance. Finally, these effects lower the dynamic range of the X-ray sensor as a detector, requiring renewal of the sensor when its detection level falls below specified value. Aging of the X-ray sensor explained above depends on the total amount of received X-rays and, consequently, the key to extending the life of the X-ray sensor is reducing the total amount of radiated X-rays. As a result, using low-output X-ray generators reduces the total amount of X-rays beams and extends the X-ray sensor life.

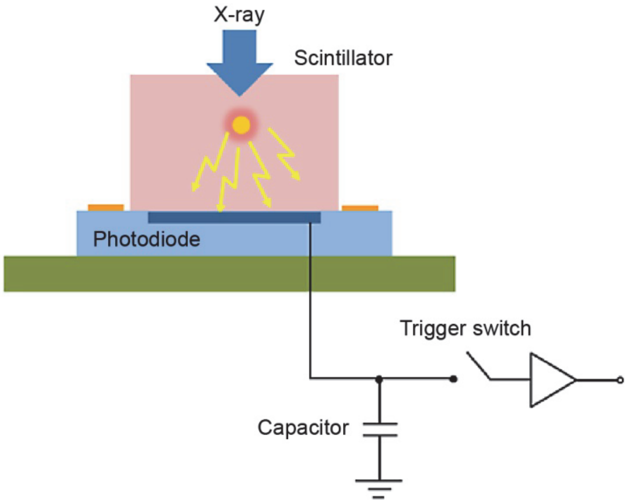


Figure 4 Principle of X-ray Inspection Machines

2.4 X-ray Generator Heat Generation

Anritsu's X-ray generators are mounted in a vessel filled with insulating oil. This oil not only insulates the X-ray tube which has high impressed voltages of about 100 kV but also plays a secondary cooling role by paying as a heat sink/radiator for heat radiated from the X-ray tubes. Figure 5 shows the basic structure of the X-ray generator. As shown, The X-ray tube is mounted in position so the radiated X-ray beam is aligned with the beryllium window in the bottom face of the oil-filled vessel. The oil in the vessel completely covers the X-ray tube. Cooling fins mounted on the top of the oil-filled vessel releases the heat and ensure that the oil temperature does not exceed the permitted level. The insulating oil becomes carbonized gradually due to the high temperature then eventually loses the insulation properties. This effect is faster at higher temperatures, making it necessary to change the oil as the insulation performance decreases. Preventing degradation of the insulating oil extends the life of the X-ray generator, ultimately cutting the running costs. As a consequence, a key issue is designing an X-ray inspection system that completes operation with a lower X-ray tube output.

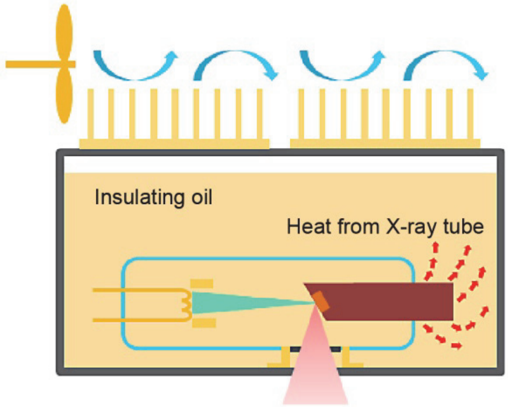


Figure 5 Structure of X-ray Heat Source

3 Development Points and Implementation

The fundamental purpose of the development was to re-examine the performance of the X-ray generator and X-ray sensor to extend its lives and cut overall running costs. The following sections explain the actual application. In addition, the system operation screens were also improved and particular examples of screens indications are also explained.

3.1 Extending Life

Of all the parts in the X-ray inspection system, the X-ray tube has the shortest life. As explained earlier, there are two failure modes; the most important is the occurrence of electrical discharges due to the decreasing in vacuum, which causes unstable X-ray generation. The first obvious countermeasure is to improve the quality of the materials used to manufacture the X-ray tube to help prevent loosing the vacuum. This upgrade requires careful selection of tube materials and many engineering hours at the X-ray tube production stage. Moreover, this method has cost issue and yield limitations and is not an effective solution. Another method is to apply less power to the X-ray tube which directly associates with slowing down the loss of vacuum, in other words, take life extension measures. This method lowers the X-ray tube output as far as possible to reduce outgassing inside the tube. In concrete terms it means suppressing the current in the X-ray tube filament to suppress gas generation. Consequently, our main development goal this time was to develop an X-ray inspection system using a low X-ray output.

Implementing an X-ray inspection system satisfying the above goals requires compensating much less detection sensitivity caused by the lower X-ray output, which necessitates increasing the detection sensitivity of the X-ray sensor. Achieving this technology was critical factor to successful development of this X-ray inspection system. We ran repeated trial-and-error tests and were finally succeeded in developing an X-ray sensor with sensitivity forming the core technology in maintaining the same sensitivity as predecessor X-ray inspection systems while reducing the X-ray tube output. Figure 6 shows a schematic of the developed sensor in the newly developed X-ray inspection system. As shown, the sensor sensitivity has been improved two-fold by cutting the heat generated from the X-ray tube, extending the life of the X-ray tube by a factor of 3.

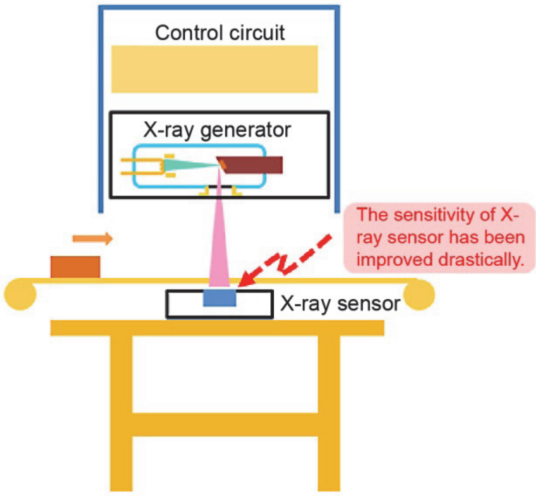


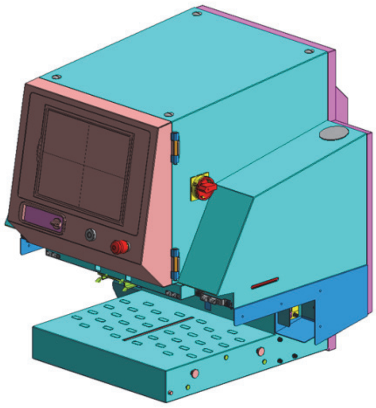
Figure 6 Sensor Schematic

3.2 Thermal Design

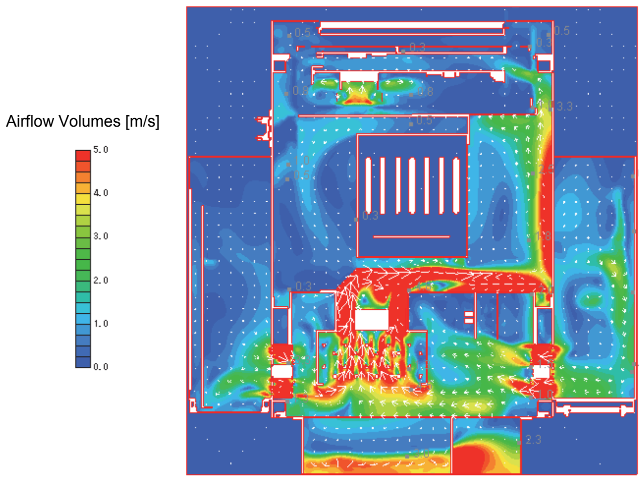
Reducing the X-ray tube output and the heat generation from the tube lead us to wide-ranging simplification of the system's heat generation. Specifically this development cut the amount of generated heat by 30%. In addition, it was also possible to eliminate the cooling equipment used in previous designs by implementing a new simulation-based thermal design. This section explains the thermal design simulation.

Figure 7 shows an example of using fluid analysis simulation when designing the main parts of the X-ray inspection system. Thermal design was used widely to simulate and analyze thermal flows based on finite element analysis, resulting in implementation of the cooler-less solution. Figure 7(a) shows the main parts including the system sensor section. Simulating this shape enabled total analysis and design, such as visualizing heat distribution and fan airflow to move on its final design. Figure 7(b) shows an example of the fluid analysis simulation; parts in red indicate zones with high airflow volumes. We concluded the final design based on numerical comparison of position of fans and its airflow efficiency within the system.

As described above, utilizing simulation for thermal designs during actual development tremendously helped optimizing the control of ventilation; combination of reducing heat generation and reducing the output of the X-ray generator, brought us to cooler-less design. In addition, running costs are drastically reduced due to the lower power consumption.



(a) Diagram of Key Parts



(b) Example of Fluid Analysis

Figure 7 Fluid Analysis Simulation Example

3.3 Improving Operability

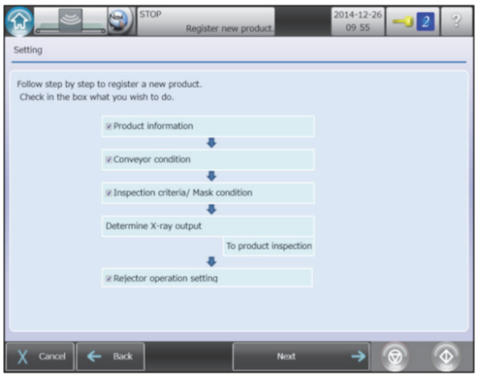
While working on the new design of the system, we also upgraded its operability. This article introduces two examples. First, we added a new auto-setting function. Table 1 compares the newly developed auto-settings with the predecessor system. The functions listed in Table 1 are the main functions for optimum operation of the system. Previous systems had only two basic functions that could apply auto-setting: 1. Contaminant detection, and 2. Virtual weight inspection, however the other nine settings had to be manual setting performed individually as needed. In contrast, the newly developed system can use the auto-setting to other 6 functions including setting masks according to the inspection target, detecting the number of products and missing products, detecting products with packaging errors, etc., simplifying the operator's work.

Table 1 Auto-set Functions

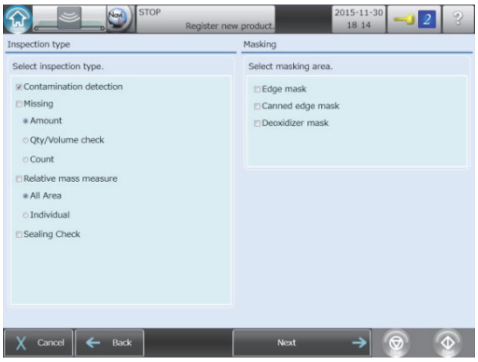
Yes: supported No: not supported

No.	Function	New X-ray Inspection System	Previous X-Ray Inspection System
1	Contaminant Detection	Yes	Yes
2	Virtual Weight Inspection	Yes	Yes
3	Edge Mask	Yes	No
4	Canned Edge Mask	Yes	No
5	Deoxidizer Mask	Yes	No
6	Missing Product Detection	Yes	No
7	Product Count	Yes	No
8	Sealing Check (Area)	Yes	No
9	Split Shape Inspection	No	No
10	Broken Shape Inspection	No	No
11	Sealing Check (form)	No	No

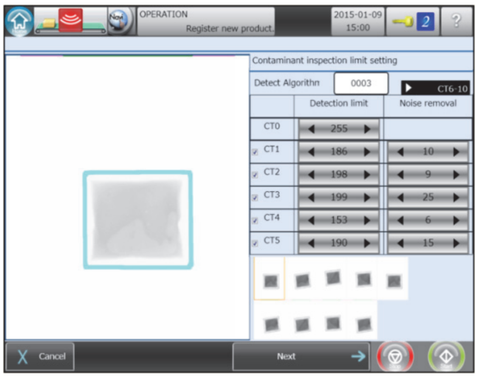
Figure 8 shows examples of auto-setting and auto-setting screens for inspected retort curry pouches. The initial screen (a) in the figure is for auto-setting. It shows the process flow. Screen (b) shows the selection of inspection type and masks. Screen (c) shows the result of image processing algorithm. Screen (d) shows the final auto-setting contents and confirmations. These auto-setting functions eliminated the complex manual settings and considerably improved work efficiency.



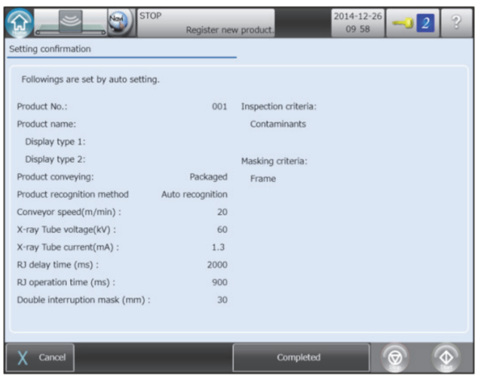
(a) Initial Screen



(b) Inspection Items and Mask Function Settings



(c) Algorithm Auto-setting for Retort Curry Inspection



(d) Auto-setting Contents Notification Screen

Figure 8 Examples of Auto-setting Screens

On top of additional auto-setting function, we also re-examined the hierarchical structure of the operation screens with the aim of minimizing the number of transitions between steps. As a result, this newly developed system is much easier to handle, less setting steps. Table 2 lists a comparison of this change between the conventional model and new model as the number of screen touches and screen transitions, both of which are nearly cut in half. Moreover, the time required for setting has been reduced by about 65%.

Table 2 Effect of Changing Screen Hierarchies

Item	New X-ray Inspection System	Old X-ray Inspection System
Number of screen touches	58 times	110 times
Number of Screen Transitions	15 times	41 times
Setting Time	20 sec	62 sec

As explained above, the new operating screen hierarchy is based on the principle that an operator can complete setup without needing to refer to the operation manual. We are confident that it successfully delivered much improved operability compared to previous systems as the outcome of this redesign.

4 Main Specifications

Figure 9 shows the dimensions of this newly developed X-ray inspection system and Table 3 lists the main specifications.

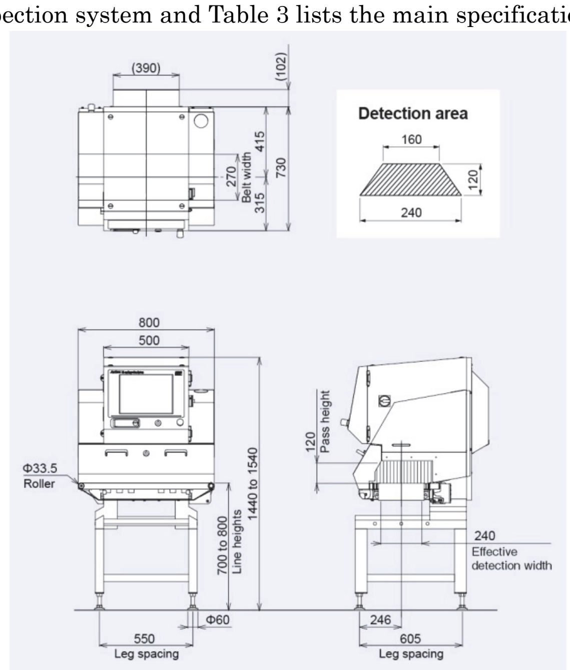


Figure 9 External Structural Diagrams

5 Summary

Food-processing industries have required much longer life expectancy on X-ray inspection systems. Having the production line to be unexpectedly stopped will cause a major negative impact on production efficiency and eventually affects production costs considerably. Moreover, replacing those expensive parts increases the running costs which has a major impact on the customer's budget. To solve these issues, we have developed a new long-life X-ray inspection system by combining a newly developed high-sensitivity X-ray sensor with the previously used X-ray generator. This system can reduce the output of the X-ray generator compared to previous systems, which lead to reducing damage to the X-ray tube and X-ray sensor and helps extend the life of these two key parts, extending the life of entire system. Additionally, reducing the output of the X-ray generator lowered generated heat, enabling elimination of cooling equipment required in previous designs hence achieved cooler-less specification. For that, reduces power consumption by 30% and helps cut running costs by more than 20%.

We are aware that the development of this system has only helped solving some customer requirements, but we are eager to continue looking at further improvements to support other needs.

References

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Table 3 Main Specifications

Model	KXS7522AWCLE	KXS7522AVCLE	KXS7534AWCLE	KXS7534AVCLE
X-ray output	Tube voltage 30 to 80 kV, tube current 0.4 to 3.3 mA, output 12 to 100 W			
Safety	X-ray leakage maximum 1.0 µSv/h or less, prevention of x-ray leakage by safety devices			
Display	15-inch color TFT LCD			
Operation method	Touch panel (with touch buzzer)			
Product size	Maximum width 240 mm, maximum height 120 mm		Maximum width 390 mm, maximum height 220 mm	
Belt width	270 mm		420 mm	
Preset memory	200			
Belt speed/ Maximum product weight	10 to 60 m/min, maximum 5 kg		10 to 60 m/min, maximum 5 kg	
	60 to 90 m/min, maximum 2 kg		—	
	10 to 40 m/min, maximum 10 kg (optional)		10 to 40 m/min, maximum 10 kg (optional)	
Power requirements	100 to 240 VAC, single phase, 50/60 Hz, 700 VA or less (standard)			
Mass	250 kg	255 kg	305 kg	310 kg
Environmental conditions	Temperature: 0° to 35°C, Relative humidity: 30 to 85%, non-condensing			
Protection class	Conveyor: IP66 Other parts: IP40	Entire surface conforms to IP66	Conveyor: IP66 Other parts: IP40	Entire surface conforms to IP66
Exterior	Stainless steel (SUS304)			