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CHARACTERISATION OF SEGREGATION BY DYNAMIC NEUTRON RADIOGRAPHY

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Dynamic neutron radiography is an advanced non-destructive technique to visualise and analyse different types of segregation phenomena in technically important objects. Here we describe applications on calorimetric devices studied during operation. Segregation behaviour in the water separator and formation of clogging in the tube system of absorption-type refrigerator is studied. Separation of lubrication oil on the surface of the cooling agent in the evaporator puffer of compression-type cooling units, and inhomogeneous distribution of the working fluid in thermostats is discussed.

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1. Introduction

Neutron radiography has proved to be useful tool in non-destructive testing investigations, and its increasing role may be observed in various applications (see e.g. [1] and therein). Dynamic neutron radiography (DNR) makes it possible to visualise the behaviour of fluids, e.g. flow, evaporation, condensation processes inside of closed metallic objects with hydrogen containing fluids [2–8]. An important application of this method is the visualisation of the inner processes of various calorimetric devices with special respect on segregation phenomena.

In this overview we give a brief description of the DNR method and of the experimental facility at the Budapest Research Reactor. Investigations are presented on three types of calorimetric devices: absorption- and compression-type refrigerators and thermostats.

2. Neutron radiography method and experimental facility

Neutron radiography is based on the application of the different attenuation coefficients of neutrons for various elements (see Fig. 1), that makes possible to receive a two-dimensional image on the composition and on the inner structure of the investigated object. The schematic view of a radiography experiment is

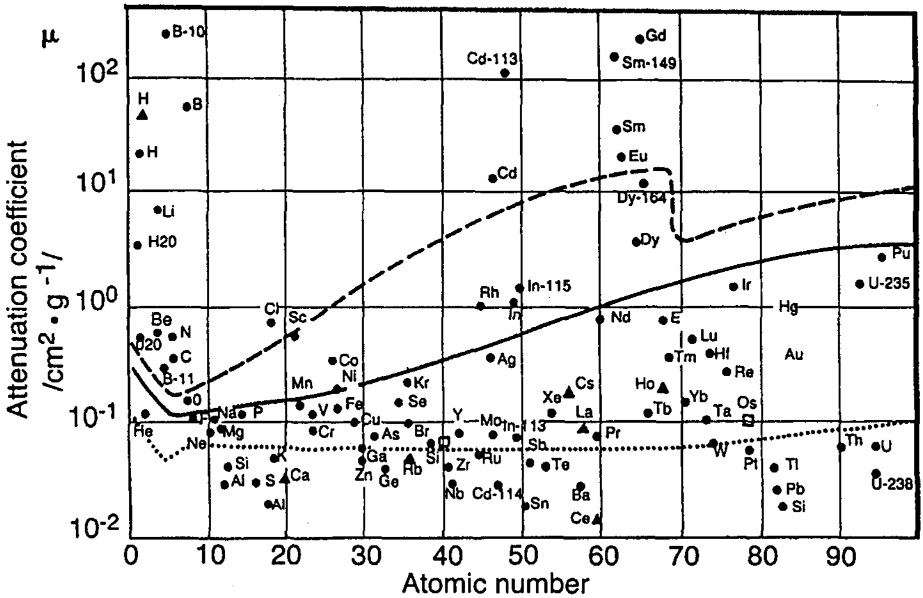

Fig. 1. Attenuation coefficient of elements for neutrons (dots or triangles), for 1 MeV gamma ray (dotted line), for 150 keV X-ray (solid line) and for 60 keV X-ray (dashed line).

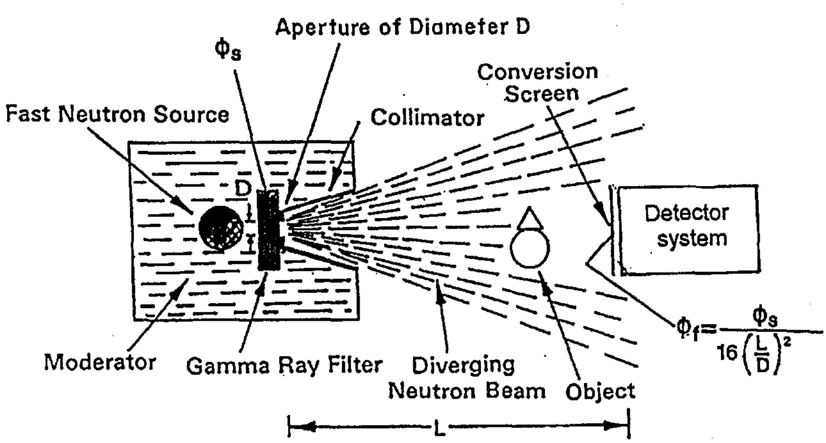

Fig. 2. Schematic experimental setup of neutron radiography.

given in Fig. 2. The image resolution achievable with the neutron beam depends basically on the beam geometry and is expressed by the L/D ratio, where L is the collimator length and D is the diameter of the inlet aperture of the collimator on the side facing the neutron source.

The DNR station at the 10 MW Budapest Research Reactor serves as a high performance experimental facility for investigation of model units and of real industrial objects under running conditions. The detailed description is given

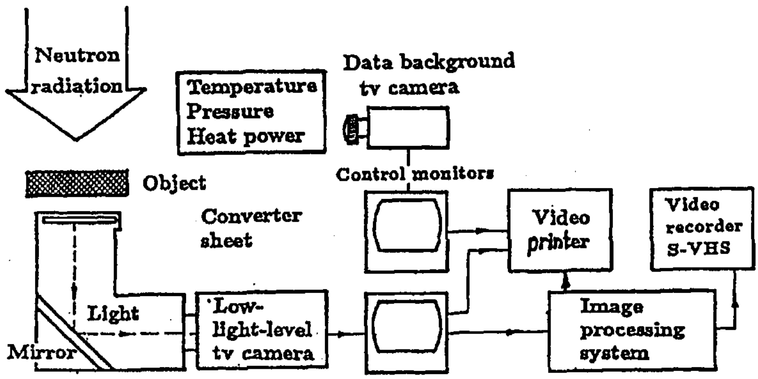

Fig. 3. The block diagram of the dynamic neutron radiography station at the 10 MW Budapest Research Reactor.

in [9, 10], here we give a brief characterisation. The neutron beam is obtained through a thermal channel of the reactor using a pinhole type conical collimator. The collimation ratio is $L/D = 170$, the beam diameter is 150 mm and the neutron flux is 10^8 n/(s $\cdot$ cm^2) at the object position. Objects under investigation with a weight of up to 250 kg and surface area of 700×1000 mm^2 can be moved into the correct position of the beam by means of a remote control mechanism.

The schematic block diagram of the DNR station is shown in Fig. 3. The transmitted neutron image of the object is converted into light by a scintillation converter screen (type NE 426) and the "light image" is detected by a low-light-level camera (10^{-4} lux for type TV 1122 or more recently a CCD camera is used with 10^{-5} lux sensitivity). The imaging cycle is 40 ms, thereby providing the possibility for visualising medium speed movements up to about 2.5 m/s inside the investigated object. The resolution of the detected radiography image is ≈ 150 μm.

The radiography images are displayed on a monitor, stored by an S-VHS recorder and for further analysis an image processing system is used (type Sapphire ver. 5.05 by Quantel). In addition to the radiography image other parameters characterising the operation of the investigated object — such as operating time, pressure, temperature, flow velocity, power consumption — are measured and recorded.

3. Investigated calorimetric devices

3.1. Absorption-type refrigerators

Aggregators of refrigerators or even complete boxes were placed into the neutron beam. The working fluid of an absorption refrigerator contains 35% NH_3 dissolved in water, it is known as a rich solution. Because of the high hydrogen content of the circulating material, the working process can be well visualised by neutron radiography. A functional model of an absorption aggregator is shown in Fig. 4. Rich solution flows from the tank through the heat exchanger into the boiler where it is heated to about 170°C. At this temperature ammonia gas separates

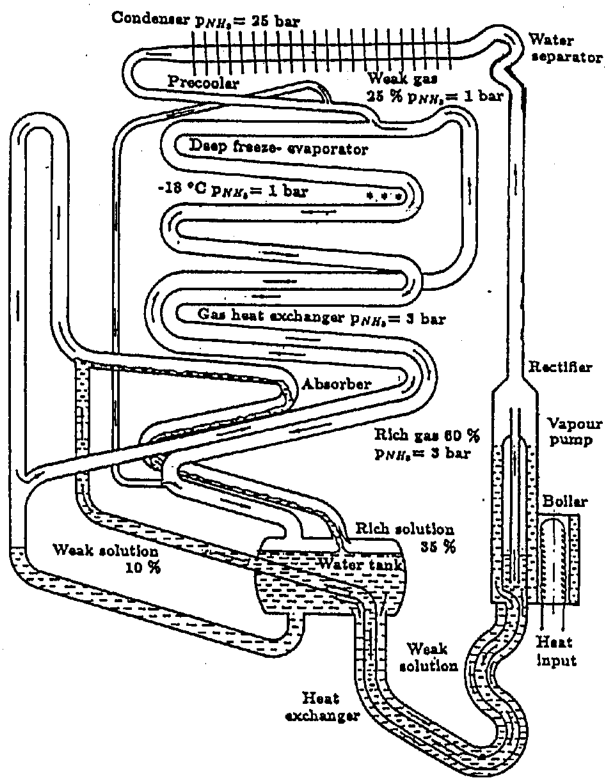

Fig. 4. Functional model of an absorption-type refrigerator.

from the water, goes through the vapour pump taking up water drops with it. Most of this water gets back as a weak solution — with an ammonia content of about 10% — to the absorption tube system through the heat exchanger. The remainder of the aqueous water condenses in the water separator and flows back to the rectifier. The practically pure, 70°C ammonia vapour gets into the condenser where the temperature is about 20°C and the pressure is 25 bar. Under such conditions the ammonia vapour condenses. This ammonia fluid is blown by 25 bar hydrogen or helium, meanwhile it evaporates refrigerating its surrounding in the deep-freeze unit. It gets back to the fluid tank through the absorber tube system, meanwhile it is absorbed by the weak solution and the cycle process starts again. Absorption refrigerators contain no moving parts and work without any noise. As they consist of steel tubes of 1.5 mm wall thickness, the inner processes can easily be visualised by neutron radiography.

3.2. Compression-type refrigerators

The schematic layout of a compression-type cooling unit is shown in Fig. 5. The compressor, which is lubricated and cooled by oil, pumps the freon into the condenser at 20 bar. The pre-cooled gas passes through the capillary to the evapo-

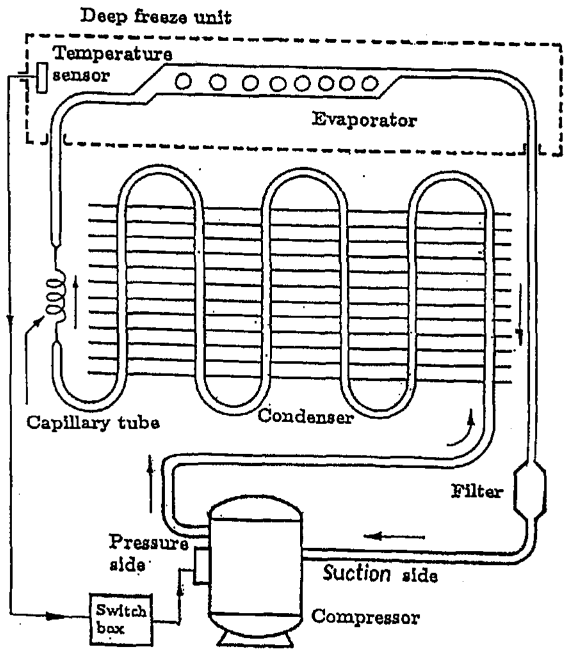

Fig. 5. Functional model of a compression-type refrigerator.

rator system. The liquid freon evaporates in the flat tube system of the deep-freeze unit meanwhile it refrigerates its surroundings. The gas returns to the compressor on the pumping side through a filter. This cooling unit consists of copper and aluminium components of about 1 mm thickness. Thus the inner stream processes may be visualised. However, measurements during operating conditions may be performed on units covered by a heat insulator, which slightly decreases the quality of the radiography image.

Recently, great efforts have been done by manufacturers to develop new constructions of compression-type refrigerators based on the use of environmental friend R-134a freon cooling agent instead of the previously used chlorofluoro-carbons (CFCs). The CFCs are one of the so-called "greenhouse" gases and so may be relevant to the problem of global warming of the earth, although their significance is likely to be comparatively minor. Many CFCs were used as working fluid in refrigerators, freezers and air-conditioning units. The development of safe, effective substances is one of the most difficult challenge facing industry throughout the world. Much work has been focused in the last decade on finding suitable ozone-benign replacement material. According to the Montreal Protocol (1986) which was formulated on the International Conference "Saving the Ozone Layer" the following rates for CFCs products reduction were accepted: "in year 1993 — consumption cut to 80% level, and in 1998 — consumption cut to 50% of the 1986's level, and similar cuts in production".

3.3. Thermostats

Most of the thermostats consist of a cylindrical sensor filled up with fluid and of a membrane connected by a capillary to each other. When the temperature of the sensor increases, the fluid in the cylinder expands, and the increased pressure transfers the fluid to the membrane through the capillary. The membrane is connected to an electronics that controls the heating power of the corresponding object.

4. Results by dynamic neutron radiography

4.1. DNR measurements on absorption-type refrigerators

The water separator (see Fig. 4) is one of the most important part of the device because at this point occurs the separation of the ammonia gas from the accompanying water vapour coming from the boiler. The segregation occurs in the consequence of the combined effect of temperature decrease and gravitation movements. For the separation an optimal geometry of the tube is needed in order to decrease the temperature to the required level. The visual observation of the effect is very advantageous for the designer (Fig. 6). For several new constructions the geometry of the tube is not optimal, for instance the tube is too long, and thus not only the separated vapour (water drops) but also the cooling agent flows back to the rectifier. That can be visualised by DNR. If the cooling agent flows back to the rectifier it causes significant decrease in the cooling efficiency (about 10–15% decrease). In order to prevent the cooling down and the condensation of the cooling agent two solutions were offered: (i) the heating efficiency of the boiler was increased by about 5% that proved to be enough to prevent the pre-condensation. Its disadvantage was the increased costs due to the increased energy consumption; (ii) a more reliable solution was the application of heat insulator material around the bottom part of the separator decreasing this way the cooling surface.

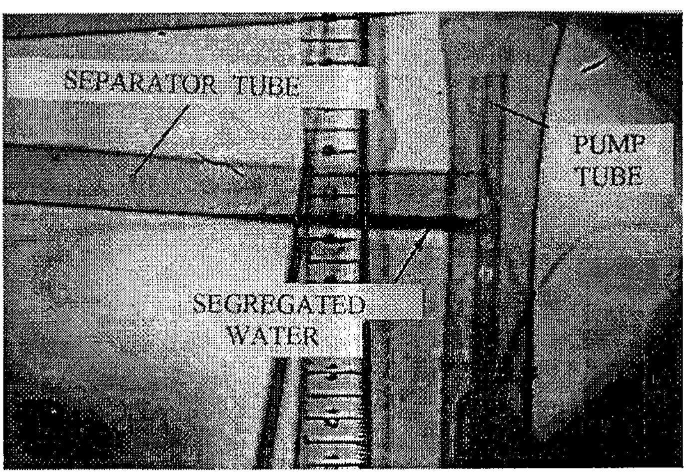

Fig. 6. Neutron radiography image of the water separator showing the condensed water that flows back to the rectifier pump tube.

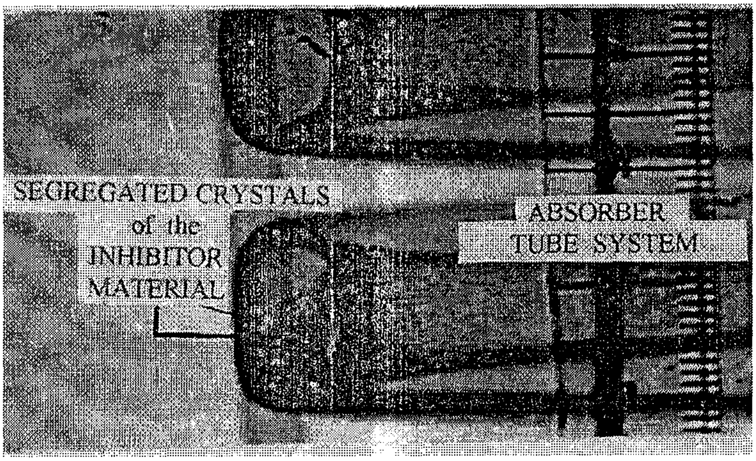

Fig. 7. Neutron radiography image of the absorber tube system with the segregated inhibitor material forming a clogging.

Another very important segregation phenomenon may occur in absorption--type refrigerators. In order to decrease the viscosity of the weak solution various suitable inhibitor materials — containing sodium chromate — are dissolved in the working fluid. If the viscosity of the working fluid is optimal, the weak solution in the absorber may absorb the evaporated ammonia gas on a large surface. Sometimes these salt crystals segregate at those points of the tube system where the flow is relatively slow (Fig. 7). In consequence, a crystallisation procedure may start at the segregation points leading to dangerous clogging and thus, to the break-down of the cooling unit. DNR visualisation enables to observe the starting segregation, the time kinetics of crystallisation process and this way to prevent the break-down of the unit.

4.2. DNR measurements on compression-type refrigerators

Dynamic neutron radiography has been used successfully in research and development of compressor type refrigerators working with the R-134a new environment friendly cooling material instead of CFCs products. The problem with the new R-134a freon cooling agent is that its oil solvable capability is smaller than that for the previously used R-12, and this causes several problems in the newly developed constructions. Visualisation and analysis of internal processes provide useful information for experts in development of new prototypes or to find the reason of defective functioning. It is very important to know the segregation points; these may be visualised by neutron radiography. Figure 8 shows the segregation of the synthetic lubrication oil on the surface of R-134a cooling agent in the evaporator puffer. This thin layer hinders the evaporation of R-134a leading to the decrease in the cooling efficiency, and it is missing from the lubrication process of the compressor bearing as well. As a result of the DNR investigations the flow conditions were optimised in the puffer by changing the ratio of the cooling agent and the lubrication oil (Fig. 9).

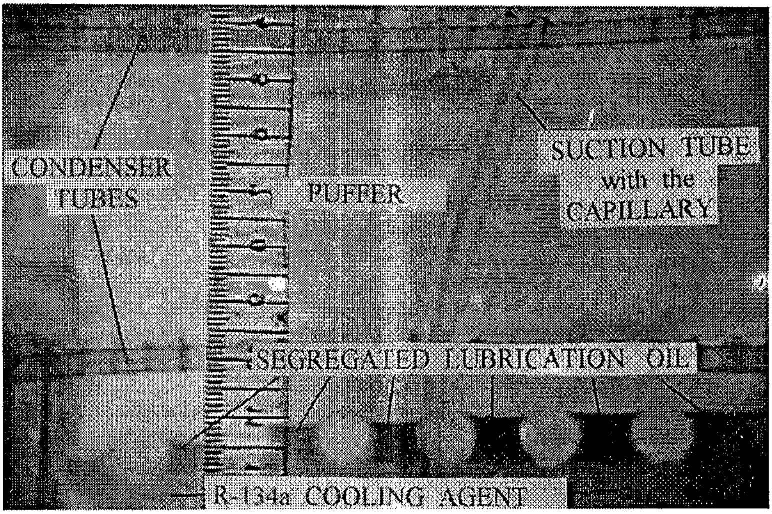

Fig. 8. Neutron radiography image of the segregated lubrication oil on the surface of the cooling agent in the evaporator puffer.

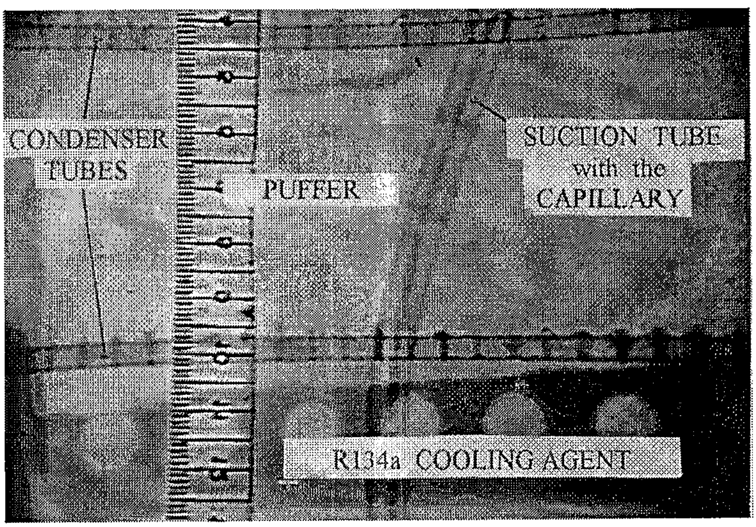

Fig. 9. The cooling agent homogeneously fills out the evaporator.

4.3. DNR measurements on thermostats

The aim of the study was to find the origin of defective functioning of a series of thermostats. Using DNR method the inner working process was visualised at different temperatures, both in the cylindrical sensors and in the membranes. The radiography images were quantified by the image processing system. Figure 10 shows the NR image of the sensors and that of the membranes at 25°C. It is

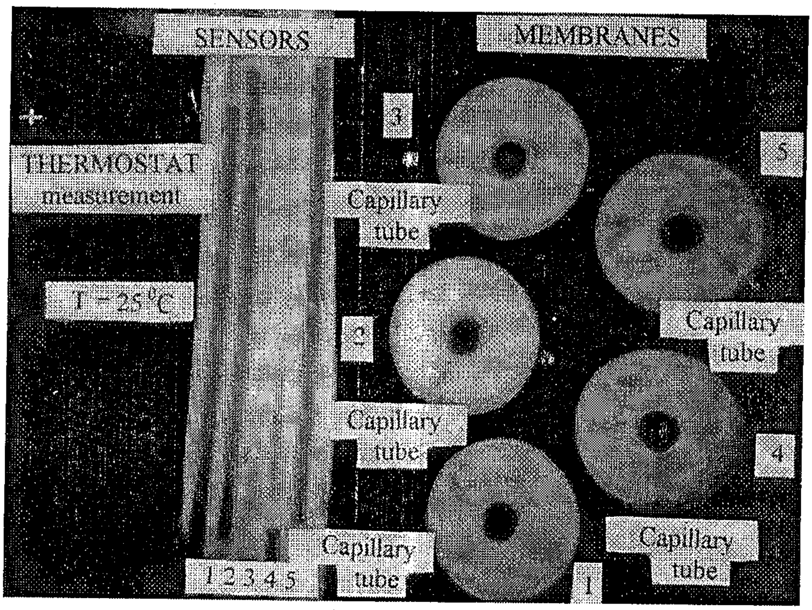

Fig. 10. Neutron radiography image of the sensor tubes and membranes for 5 thermostats (No. 1–5).

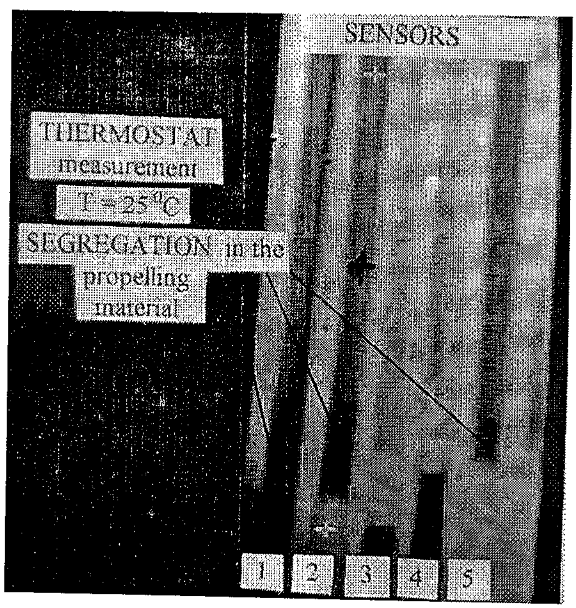

Fig. 11. The arrows show the segregation areas in the sensor tubes.

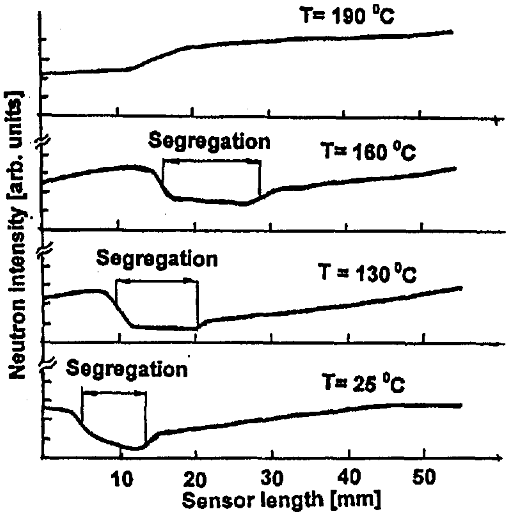

Fig. 12. Quantified neutron radiography image: neutron intensity measured along the length of the cylindrical sensor (No. 2) at different temperatures.

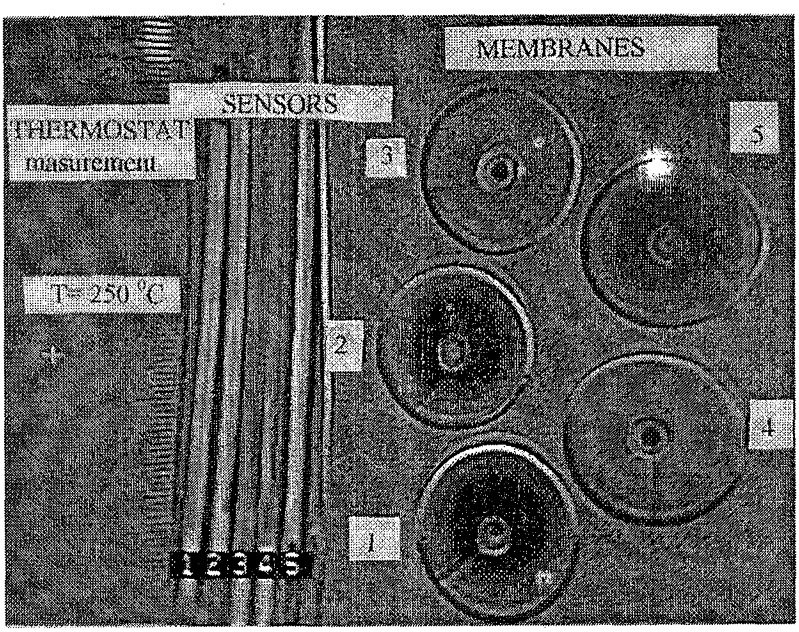

Fig. 13. "Shading neutron images" measured at 190°C (for details see the text).

clearly seen that two of the sensors are practically empty (No. 3 and 4). The other sensors are not homogeneously filled up with the propelling material, segregation areas can be seen as indicated by the arrows in Fig. 11. The quantified neutron intensity measured at different temperatures along the length of the cylindrical sensor is shown in Fig. 12 (for No. 2 sensor). The low intensity values correspond to the high neutron absorption i.e. to the more dense material that belongs to the segregation area. At 25°C a well-defined segregation area can be identified. When the temperature is increased the flow of the propelling material takes place into the membrane through the capillary. A continuous shift of the position and a broadening of the segregation area can be observed when the temperature is increased up to 190°C, meanwhile the density of the propelling fluid decreases. At 190°C the membranes are filled up with the propelling material and the sensors are filled out by the residual vapour. This situation is demonstrated on the "shading neutron image" in Fig. 13. The "shading image" shows the intensity difference between the neutron images taken at 190°C and 25°C. The grey scale corresponds to the situation when no intensity change occurs, the dark scale of the membranes (No. 1, 2 and 5) belongs to the filled up state, while the bright scale of the sensors (No. 1, 2 and 5) shows the practically empty state. Thermostats No. 3 and 4 are grey because no fluid flow occurred.

5. Summary

DNR proved to be an effective non-destructive technique to visualise and analyse different types of segregation phenomena in technically important objects. DNR investigations were performed on calorimetric devices during their operation conditions.

- Segregation behaviour in the water separator and formation of clogging were detected in the absorption-type refrigerators. On the basis of DNR observations the constructions were optimised.
- Segregation of lubrication oil on the surface of the cooling agent in the evaporator puffer in compression-type refrigerator was visualised. On the basis of the observations the ratio of the components was optimised.
- The origin of malfunction in thermostats was clarified by DNR observations.

Several types of defective functioning caused by segregation phenomena were detected and the origin became clear by the use of DNR, offering an effective tool to manufacturers to improve their products.

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