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Research Article

Test bench for gas-dynamic studies in the furnace channel for nuclear fuel pellet sintering*

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Abstract

Nuclear fuel pellets are sintered in high-temperature furnaces in an atmosphere with strictly defined requirements for the composition of the gas environments in the furnace's different temperature zones. The preset process conditions in the mixed nitride uranium-plutonium (MNUP) fuel pellet sintering furnace is achieved through the respective gas supply arrangement and by the design of the barriers between the temperature zones and that of the gas supply and discharge units. A CFD model was created in the Ansys Fluent package and validated for testing the functionality of the design concepts used to develop the MNUP fuel sintering furnace channel. A mockup of the sintering furnace channel, which makes a part of the gas-dynamic test bench, was developed and fabricated for the analytical model validation.

The paper presents a description of the test bench design and performance for measuring the concentration of gases in the channel simulating the nitride nuclear fuel sintering furnace channel. The results of the test bench gas-dynamic studies were used for the computational and experimental justification of the approaches used to develop the sintering furnace channel. The functionality of the barriers for the sintering furnace channel division into zones with the preset composition of the gas environments and the gas supply and discharge units has been tested experimentally. The obtained experimental data on the distribution of the process gas concentration makes it possible to validate computational thermophysical and gas-dynamic CFD models of the MNUP fuel sintering furnace channel.

Keywords

gas-dynamic studies, sintering furnace, furnace channel, furnace zone, MNUP fuel, gas distribution modeling, gas concentration measurement, gas sampling, barrier

Introduction

An advanced nuclear fuel type for fast neutron reactors is the so-called dense fuel having a density higher than that of uranium dioxide (UO_2) used predominantly at the present time. Mixed nitride uranium-plutonium (MNUP) fuel, UPuN, is proposed for use in the BN-1200 and BREST-OD-300 reactors (Bezzubtsev et al. 2002, Yeliseyev et al. 2013, Adamov et al. 2015).

The Pilot Demonstration Energy Complex (PDEC), including a uranium-plutonium nitride fuel fabrication/refabrication module (FRM), is being built at the site of JSC Siberi-

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an Chemical Combine as part of the *Proryv* project (Denisov et al. 2017). One of the key operations in the process of the fuel pellet fabrication for fuel elements is pellet sintering (Bernard et al. 1987). The purpose of sintering is to improve the physical and mechanical properties of pellets, that is, to increase their density and mechanical strength. Normally, fuel pellets are sintered commercially in high-temperature horizontal pusher-type furnaces in which pellets, when in the furnace channel, move successively through three (heating, sintering and cooling) zones (Silva et al. 2012).

The uranium dioxide sintering technology and equipment are well-proven and have been used successfully for decades, but there is no currently experience of the MNUP fuel pellet sintering on a commercial scale (Reshetnikov et al. 1995, IAEA-TECDOC-1686). Despite extensive experience gained in the manufacturing of MNUP fuel in laboratory conditions (Troyanov et al. 2014, Arai et al. 1989, Streit and Ingold 2005, Ganguly et al. 1991), the following difficulties exist for the technology of sintering this fuel to be implemented commercially:

- the need for ensuring the preset composition of the gas environments in different temperature ranges of the sintering cycle to prevent the formation of $(U, Pu)_2N_3$ not fit for commercial use;
- no leak-tight equipment for the MNUP fuel fabrication chain with an inert environment. Powders of uranium and plutonium nitrides are pyrophoric and ignite spontaneously in an aerial environment. All fabrication processes preceding the final stage of the UPuN pellet sintering shall be run in an inert environment with a content of oxygen and water not more than 50 ppm.

UPuN pellets are sintered at higher temperature (~ 1950 °C) than UO_2 pellets (~ 1870 °C). UPuN pellets are sintered in a reducing atmosphere of an argon, nitrogen and hydrogen gas mixture with stiff requirements imposed on the compositions of the gases: MNUP fuel shall be heated and cooled in an argon atmosphere with a nitrogen content of not more than 0.1 vol. %, and sintered in a nitrogen-argon-hydrogen atmosphere with a nitrogen content of not less than 50 vol. %(Denisov et al. 2017, Alekseev and Zaytsev 2013).

Therefore, two essential tasks need to be addressed in developing a pusher-type furnace for the UPuN pellet sintering: first, the required temperature field shall be achieved within the furnace channel, and, second, the channel's inner volume shall be divided into three zones with different gaseous atmospheres without using any gate valves or baffle plates to shut off the furnace channel. Operation of a furnace with radioactive substances and no visual control of the sintering furnace channel's closed volume do not make it possible to use the existing approaches in other industries (Silva et al. 2012, Feldbauer 2006). In this connection, new designs have been proposed to ensure the preset composition of the gas environment in the temperature zones of the MNUP fuel pellet sintering channel.

A gas-dynamic model of the furnace channel was developed in the Ansys Fluent CFD package to develop and justify the design of the MNUP fuel pellet sintering furnace and operating conditions (Ansys Inc. 2011, Leshchenko et al. 2017). To validate the computational model, a mockup of the furnace channel, which is a part of the test bench for gas-dynamic studies, was developed and manufactured. The mockup simulates the inner dimensions of the sintering furnace channel at a scale of 1:1. Such methods of analytical and experimental research on the distribution of the concentration of the gas mixture components in systems, where mixing of gases needs to be taken into account, are a common practice (Ying et al. 2014, Miaoren et al. 2008, Zavila and Blejchai 2017, Zavila et al. 2011).

The paper describes a test bench for gas-dynamic studies on the gas flowing and mixing processes in the sintering furnace channel mockup. It was used for the analytical and experimental testing of the proposed solutions for ensuring the preset composition of the gas environment within the MNUP fuel pellet sintering furnace channel.

Design solutions to ensure preset composition of the gas environment in the furnace channel for the MNUP fuel pellet sintering

The MNUP fuel pellet sintering furnace channel (Fig. 1) is formed by the inner surface of the lining (thermal insulation) designed as a brickwork of ceramic materials. Nuclear fuel pellets are placed in rectangular-shaped boats positioned on supporting plates. The supporting plates are used to prevent the boats from contacting each other which reduces the probability of their deformation and to

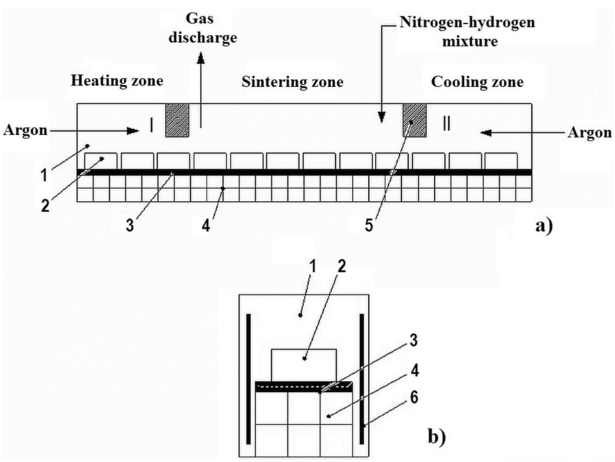

Figure 1. A simplified diagram of the sintering furnace channel with the gas supply flowchart: longitudinal (a) and transverse (b) sections: 1 – channel; 2 – boat with pellets; 3 – supporting plates; 4 – sliding brickwork; 5 – barrier; 6 – heater

transfer forces from the pusher mechanism throughout the supporting plate chain.

The temperature field inside of the furnace channel is formed by standalone multi-section electric heaters positioned vertically near the channel side walls. The furnace channel is divided into a heating zone, a sintering zone and a cooling zone which shall have definite temperature and an atmosphere with the preset composition to be kept in them.

A number of design solutions was adopted in the sintering furnace development to separate the gas environments in the furnace channel:

- argon is supplied from the preheating zone side (the boat entry into the channel) and the cooling zone side (the boat exit from the channel);
- the furnace channel is equipped with two barriers which separate the preheating zone from the sintering zone (barrier I, Fig. 1a) and the sintering zone from the cooling zone (barrier II, Fig. 1s) and shut off the upper and lateral parts of the flow area in the channel to ensure enough space for the boat movement in the channel's lower part;
- the nitrogen-hydrogen mixture is supplied into the sintering zone from the barrier II side (against the movement direction of the boats with fuel pellets);
- gases are discharged from the furnace channel near barrier I in the sintering zone.

The efficiency of the gas environment separation inside of the furnace channel is defined by the design of the barriers and by that of the gas supply and discharge units, as well as by the process parameters (temperature distribution across the channel, argon and nitrogen-hydrogen mixture flow rate, gas pressure within the furnace channel).

Test bench for gas-dynamic studies

The test bench for gas-dynamic studies was built to test the proposed designs. The test bench comprises a sintering furnace channel mockup and a gas supply, discharge and concentration measuring system (Fig. 2). The mockup reproduces the inner dimensions of the MNUP fuel sintering furnace channel with regard for the supporting plates with fuel pellet containing boats positioned inside.

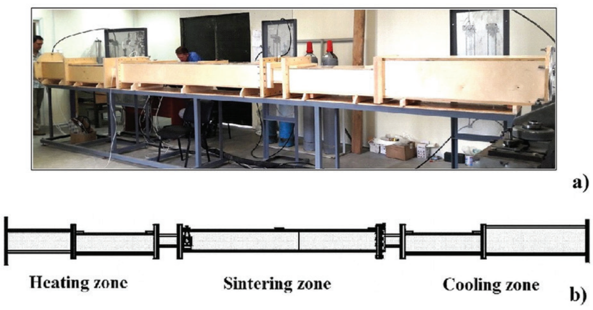

Figure 2. Overall view (a) and zone designations (b) of the sintering furnace channel mockup

The chain of the pellet containing boats on supporting plates is simulated by a monolithic rectangular parallelepiped throughout the furnace channel mockup. There are mockups of heaters intended for detailed simulation of the furnace channel shape and not used for the channel mockup heating between the sliding brickwork and the mockup side walls, that is, all measurements are performed at room temperature.

Oxygen, which is much technically simpler to record in argon, was used instead of a nitrogen-hydrogen mixture during the test bench experiments. Since the thermophysical parameters of oxygen are close to the nitrogen parameters, the gas-dynamic processes take place in the furnace channel mockup essentially in a similar way and no gas substitution affects the validation quality of the sintering furnace channel gas-dynamic model.

The concentration of oxygen within the channel mockup was measured using 14 sampling probes with an inner diameter of 3 mm. The probe positions in the channel mockup are shown in Fig. 3. There is one nonadjustable probe used in the preheating zone and another one used in the cooling zone (respectively probes 1 and 6), and there are four nonadjustable probes used in the sintering area (probes 2 through 5). These probes were used to sample gases at a height of 20 mm above the upper surface of the boat mockup with the supporting plates to study the distribution of the oxygen concentration throughout the mockup (*X* coordinate). There were also eight adjustable probes used in the sintering zone for the gas sampling at the preset point throughout the mockup height or across its width while changing the length of the probe section submerged into the channel mockup. The use of adjustable probes enabled more detailed measurements for studying the irregularity and peculiarities of the gas flow in the furnace channel.

Adjustable probes 7 through 12 were used to measure the concentration of oxygen throughout the channel mockup height, that is, from the surface of the boat mockup with the supporting plates ($Y = 0$ mm) to the upper wall ($Y = 90$ mm). Additionally, the oxygen concentrations below the surface of the boats were measured (from $Y = 0$ mm to $Y = -40$ mm) using adjustable probes 11 and 12. Adjustable probes 13 and 14 were used to study the distribution of the oxygen concentration across the width of the channel mockup (from $Z = 0$ to $Z = 320$ mm). Probes 10 through 13 are installed near the oxygen supply unit to the sintering zone and include three vertical probes and one

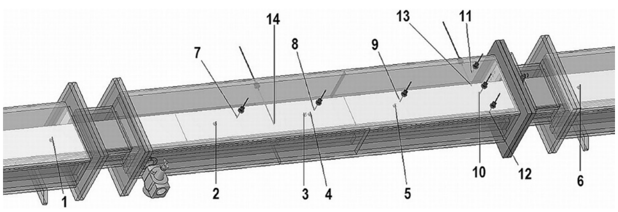

Figure 3. Positions of probes in the sintering furnace channel mockup: 1, 6 – in the preheating zone and in the cooling zone respectively; 2 – 5 and 7 – 14 – in the sintering zone

horizontal probe. Studies in this area are important since it is how the oxygen flow is formed in the oxygen supply region that defines to a great extent the oxygen movement and distribution within the sintering zone.

The concentration of oxygen in argon was measured using a GE Sensing Oxy.IQ gas analyzer with an accuracy of ± 1 % in the oxygen concentration range of 0 to 100 vol. %. The excessive pressure value was determined using a MIDA-DA-15 sensor with an accuracy of ± 0.5 % in a range of 0 to 0.16 MPa. The flow rates of the gases were measured using RM-type rotary meters with an accuracy of ± 2.5 % in a range of 0 to 10 Nm^3/h. The accuracy of the temperature determination using an SP-2 thermometer was ± 1 ºC.

Prior to the experiment, the rotary meters were verified against a Bronkhorst IN-FLOW F-202AI-M20-AGD-99-V flow regulator. This procedure is required due to the fact that rotary meters have individual calibrations of the rate scales depending on the density of the measured gas and the calibration gas which is defined by the current gas temperature and pressure.

The test bench operates in an automatic mode with all data digitized and recorded in a PC. The sampling time for all measuring channels is not more than 2 s.

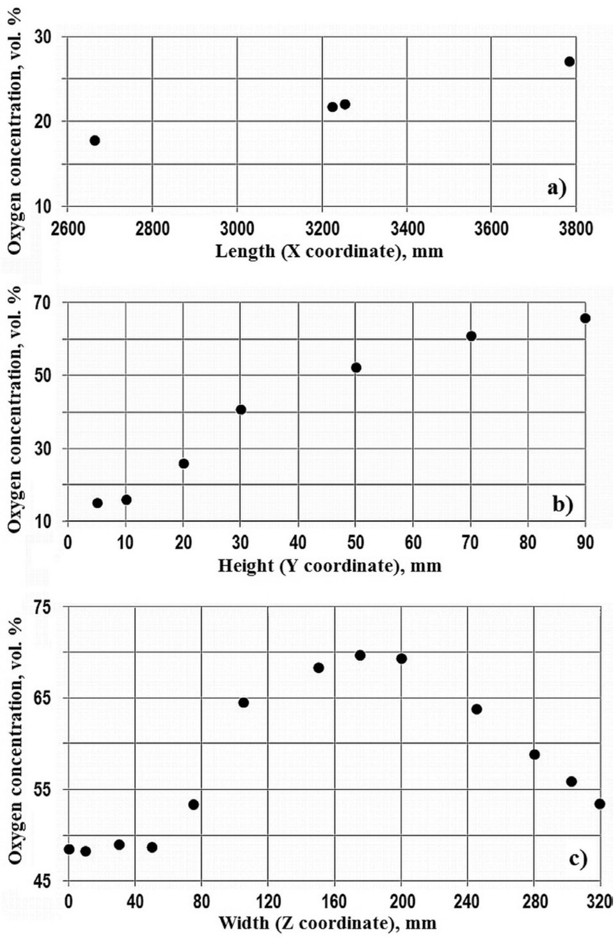

Figure 4. Measurements of the oxygen concentration throughout the length (a) and the height (b) and across the width of the sintering furnace channel mockup

The following gas supply modes can be simulated at the test bench:

- argon supply from the heating zone side – from 1 to 8 Nm^3/h;
- argon supply from the cooling zone side – from 1 to 8 Nm^3/h;
- oxygen – from 1 to 6 Nm^3/h.

The excessive pressure in the furnace channel mockup is variable in a range of 100 to 10000 Pa.

Fig. 4 presents the distribution of the oxygen concentration in argon in the sintering zone which has been obtained for the following test bench process parameters:

- the flow rate of argon on the heating zone side is 7.70 Nm^3/h, and that on the cooling zone side is 4 Nm^3/h;
- the oxygen flow rate is 4.67 Nm^3/h;
- the excessive pressure in the furnace channel mockup is 3000 ± 100 Pa (above atmospheric pressure);
- temperature of 19.5°C.

The distribution of the gases throughout the mockup length was obtained using nonadjustable probes 2 through 5 (Fig. 4a), and that throughout the height and across the width was obtained using adjustable probes 9 (Fig. 4b) and 13 (Fig. 4c) respectively.

Experimental studies were conducted in the process of which it was found that oxygen mixes with argon more intensively as the ratio of the oxygen flow rate to the flow rate of argon supplied from the cooling zone side increases from 1.2 to 1.6. The concentration of oxygen in the sintering zone increases but the concentration of oxygen in argon in the heating zone and in the cooling zone does not exceed 0.1 vol. %. (Fig. 5).

For all options of the gas-dynamic studies, the value of the oxygen concentration in the heating zone and in the cooling zone, measured using probes 1 and 6, was less than 0.1 vol. %.

The obtained experimental data on the distribution of the gases within the furnace channel mockup can be used to validate CFD models of the MNUP fuel pellet sintering furnace channel.

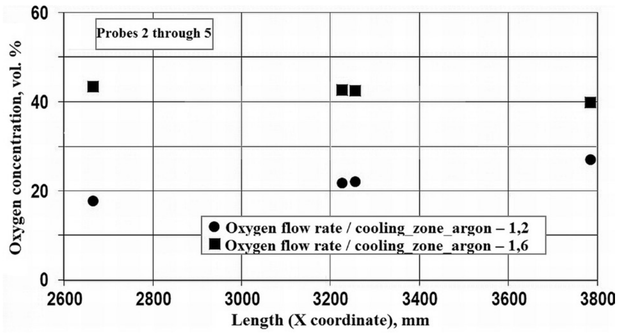

Figure 5. Results of the oxygen concentration measurement using probes 2 through 5 with a variable ratio of the oxygen flow rate to the flow rate of argon supplied from the cooling zone side

Conclusions

1. A test bench has been built which makes it possible to measure concentrations of process gases under different gas supply conditions in the MNUP fuel pellet sintering furnace channel at room temperature. The test bench is fitted with eight adjustable and six nonadjustable gas sampling probes. The design of the sintering furnace channel mockup makes it possible to use more probes to enable more detailed studies.
2. Functionality of the barriers and the gas supply and discharge units has been proved experimentally for ensuring the preset composition of the gas environment in the sintering furnace channel mockup zones. The recorded value of the oxygen concentration in argon in the heating and cooling zones was less than 0.1 vol. %. The concentration of oxygen in the sintering zone was found to increase as the ratio of the oxygen flow rate to the argon flow rate increased from 1.2 to 1.6; meanwhile, the concentration of oxygen in argon in the heating and cooling zones does not exceed 0.1 vol. %.
3. The required array of data on the distribution of the oxygen concentration in argon was obtained from the test bench gas-dynamic studies to validate the MNUP fuel pellet sintering furnace channel CFD models.

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