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THEORETICAL AND EXPERIMENTAL RESEARCH ON ADVANCED CLEAN COAL TECHNOLOGIES AT THE POWER ENGINEERING DIVISION OF THE INSTITUTE OF HEAT ENGINEERING – PFBC TEST INSTALLATION

The paper presents up-to-date results of the research on advanced coal technologies taken at the Power Engineering Division of the Warsaw University of Technology. Theoretical analyses concern mainly problems of mathematical modeling and computer simulation of combined cycle (CC), combined cycle with integrated gasification (IGCC), CC with pressurized fluidized bed boiler (PFBC) power plant operation under steady state, off-design and transient conditions. Additional information about experimental methods of investigation is provided. Detailed information about unique 3 MW_{th} PFBC test installation is presented. This plant will be used to verify results of the theoretical research.

INTRODUCTION

Several important factors caused the significant transformation of the world power industry in the last decade. The introduction of new, substantially decreased emission standards, outcomes in the rapid development of new technologies which can combine high energy generation efficiency with low emission of pollution. In the countries, where coal (especially of low quality) is the basic fuel for power systems, a growing interest in the new advanced clean coal technologies is observed [21]. The continuous improvement of gas turbines (load and efficiency) results in the fast development of combined cycle (CC) systems, which are now the dominant among new plants, built in recent years.

In Poland, the country on its way of rapid transformation towards market economy, where coal covers over 85% of domestic needs, where numerous power plants demand modernization and the new reduced emission levels are being introduced, the research on clean methods of energy generation is particularly important.

Practically in the middle of '90s two methods of advanced clean coal technologies aroused interest among potential customers in their commercial application:

- the combined cycle with integrated gasification (IGCC), in which raw or enriched coal is converted into gas supplying a gas turbine;
- the combined cycle with PFBC, in which a pressurized fluidized bed boiler is used to burn the fuel (there is a possibility of utilizing low quality coal) and in some unit configurations can substitute a gas turbine combustion chamber.

In the Power Engineering Division at the Warsaw University of Technology several theoretical and experimental studies on these topics have been undertaken. Theoretical analysis concerns mainly problems of mathematical modeling and computer simulation of the combined cycle (CC), combined cycle with integrated gasification (IGCC), CC with PFBC power plant operation under steady state, off-design and transient conditions. For example, the modernization study of a 120 MW unit, typical of the Polish power system, using IGCC with various methods of coal gasification, and the optimization of the system configuration, has been made [12]. The examination of the proposed system under off-design and part loading operation has been made [11]. The analysis has evidenced that such a method of unit reconstruction might become very attractive. The second main topic of our studies concerns designing, mathematical modeling and simulation of PFBC units. Several aspects of the application of such technology have been considered [3], [5], [7], [17], [18], [20], [24], [26], [33].

Our research does not regard only hypothetical application, but is combined with the creation of a semi-technical scale test installation. A unique PFBC test stand has been built and the latest improvements of computer control and monitoring systems are now being implemented.

1. PRESSURIZED FLUIDIZED BED BOILER TEST INSTALLATION

1.1. General installation scheme

The test installation scheme is presented in Fig. 1. The pressurized fluidized bed combustion boiler is connected with five systems: the air feeding system, the fuel and sorbent feeding system, the cooling and the flue gases removal systems. The installation is completed with measuring equipment and control elements. The main parameters of the installation and dimensions of components depend primarily on the compressor's capacity. The system was equipped with a German compressor which allows to obtain 3 MW_{th} total load and pressure 0.6 MPa.

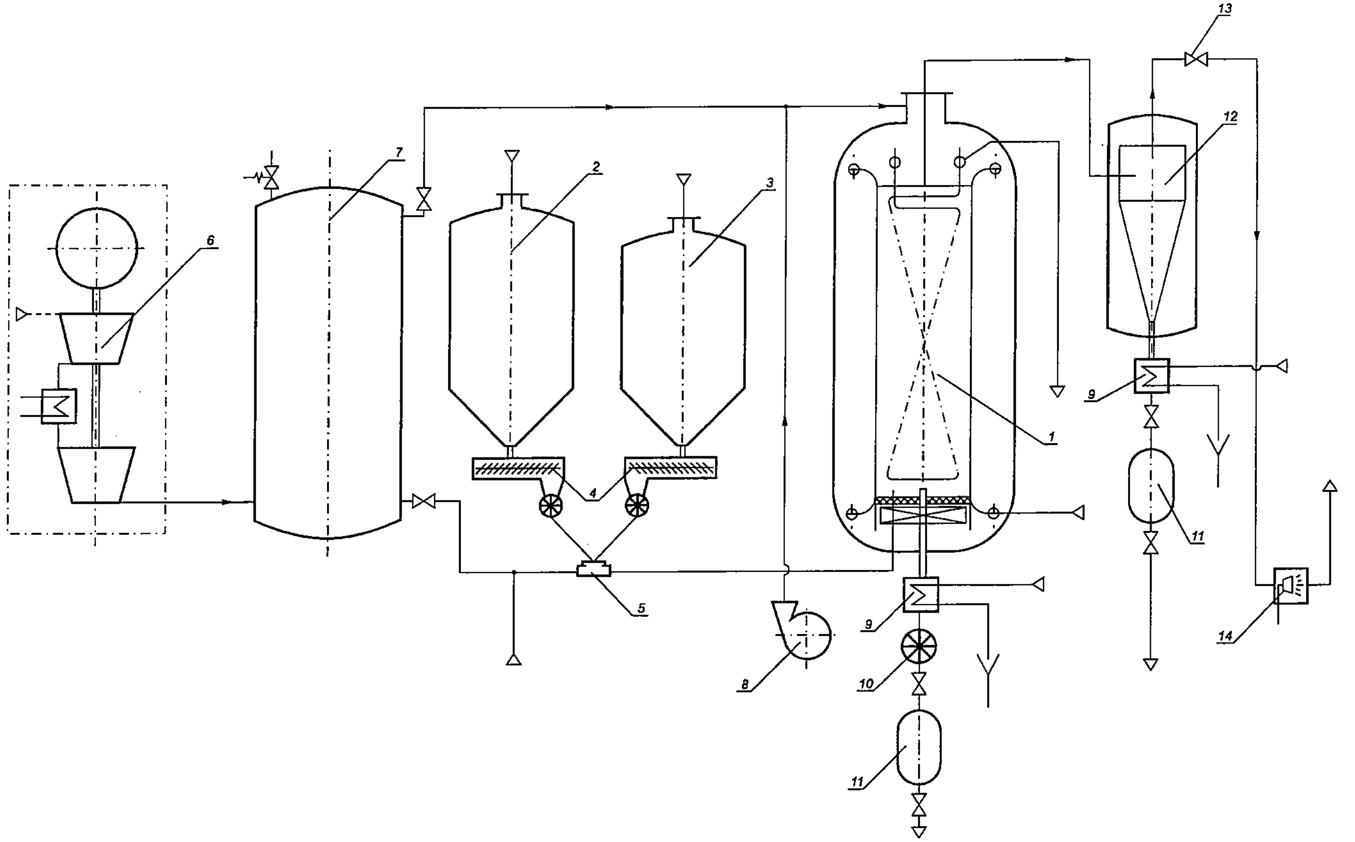

Fig. 1. The test installation diagram: *1* – PFBC boiler, *2* – coal hopper, *3* – sorbent hopper, *4* – coal/sorbent feeder, *5* – injector, *6* – compressor, *7* – equalizing tank, *8* – fan, *9* – ash cooler, *10* – ash feeder, *11* – ash storage, *12* – cyclone, *13* – pressure reducing valve, *14* – flue gas cooler

1.2. PFBC boiler

The PFBC boiler scheme is presented in Fig. 2. The PFBC water type boiler is composed of a pressure vessel and a flue, which contains fluidized bed and tubular heat exchanger (these elements were produced by SEFAKO on the basis of construction documentation designed in the Institute of Heat Engineering).

The pressure vessel internal diameter is 1400 mm, and the height is 4900 mm. The vessel is closed by elliptic covers. The upper cover is connected with the vessel blanket by flanges. The flue gases offtake with compression gland is placed at the upper cover. The air is supplied to the boiler through the flue gases outlet connection, which provides cooling for the vessel walls. At the lower cylindrical part of the vessel a ϕ700 mm manhole and passages for the start-up burner installation and measurement wires are located. The bottom cover is connected with the inlet and outlet water pipelines, fuel and sorbent feed and ash removal system. The boiler is put on four bearings attached to the lower lid.

The flue is suspended on bearings at the upper part of the vessel. It is made of tight ϕ38 mm pipe membrane walls in a 50 mm pitch. The channel section is 550×550 mm (0.3 m^2, which corresponds to 2 m/s fluidization speed and 3 MW_{th} bed power), and the height is 2870 mm. The pipes of each wall separate upper and lower chambers. There are flanges at the top and at the bottom of the channel walls.

A cover attached to the flange closes the upper flue gases outlet. The outlet flue gases conduit and a convectional heat exchanger are passed through the cover. The heat exchanger is placed in the flue. The coil exchanger is made of ϕ26.9 mm pipes in transpositional arrangement, 8 pipes in each row. There are two banks of tubes in the exchanger. The lower bank (6.5 m^2 heat surface) is immersed in the fluidized bed. The total heat surface at the fluidized bed is 9.9 m^2. The upper bank, whose task is to cool the flue gases to 500°C, has got 6.1 m^2 heat surface. The cooling water flows successively through the four flue walls and the convectional heat exchanger banks of tubes.

The flue is closed at the bottom by a cap type air distributor. The fuel conduit and the ash removal conduit are passed through the distributor plate. A gas start-up burner is attached to the distributor's air box. Its construction enables temperature changes within a big range.

The PFBC boiler's total height is 5450 mm.

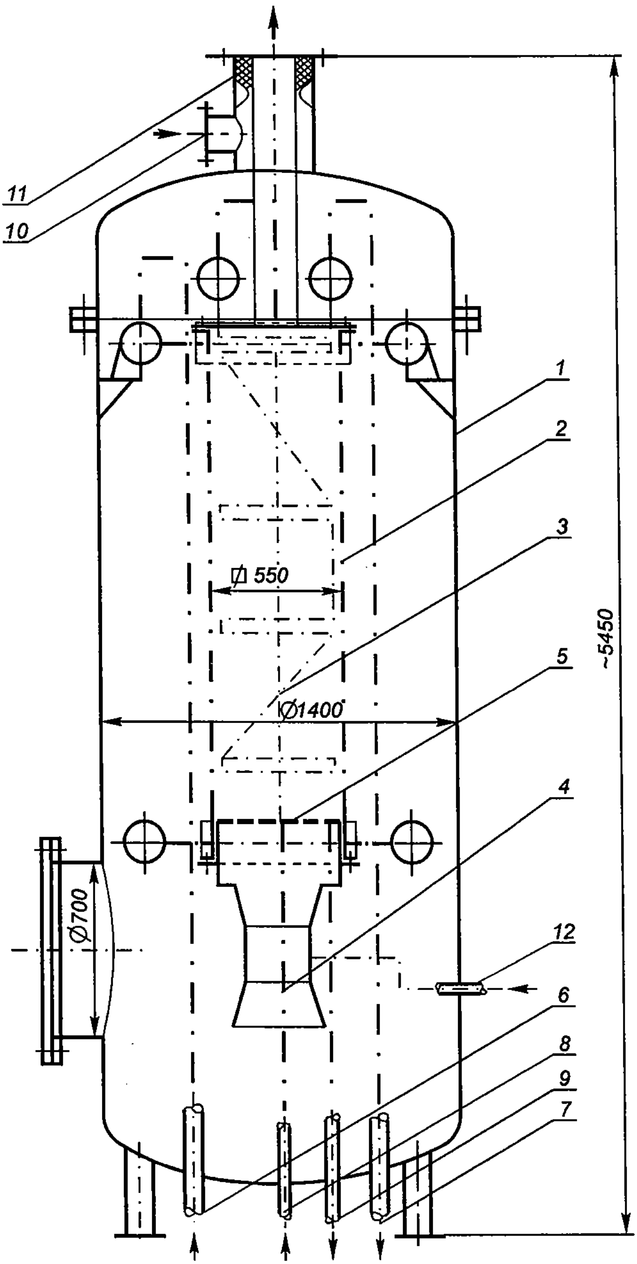

Fig. 2. The PFBC boiler diagram: *1* – pressure vessel, *2* – tube-walled flue gases pass, *3* – tubular heat exchanger, *4* – gas start-up burner, *5* – air distributor, *6/7* – water inlet/outlet, *8* – coal and sorbent feeding, *9* – bedmaterial drain, *10* – air inlet, *11* – flue gases outlet, *12* – start-up burner feeding

1.3. Flue gases path

The flue gases from the boiler are conducted to a pressure vessel, which contains a dust extraction system. In the first stage the flue gases go through a cyclone-type dust collector built in the vessel. A pressure reducing valve is placed after the vessel. From there the flue gases, after going through the cooling spray water, are conducted to a stack. The flue gases path pressurized elements are made of austenitic steel.

1.4. Air feeding system

The chamber rotary compressor (output 2510 m^3/h, forcing pressure 0.7 MPa, with the intercooler and aftercooler) is the main element of the air feeding system. From the compressor the air is conducted to an equalizing tank, afterwards through a control valve to the boiler inlet. The air feeding the fuel and sorbent pneumotransport system is supplied from the Institute's pressurized air network (auxiliary feeding of the equalizing tank with about 500 Nm^3/h from that source is possible).

1.5. Fuel and sorbent feeding system

The pneumatic pressurized fuel and sorbent feeding system is composed of the following elements:
- coal bunker, volume 5.8 m^3,
- sorbent bunker, volume 1.8 m^3,
- two attached feeders (series connected worm feeder and chamber proportioned one, driven by electric motors with regulated rotational speed),
- air jet pump for pneumatic transport,
- fuel and sorbent conduit to the fluidized bed.

Fuel and sorbent feeders are attached to the bunkers. There are cutting dampers at the inlets of the feeders. The chute conduits of the feeders are connected above the jet pump. The internal volumes of the bunkers are connected with the air volume of the boiler by equalizing conduits.

1.6. Control and monitoring system

Advanced digital system of measurements is being implemented. The installation has about 50 measurement points, connected to a central computer. On-line installation performance monitoring, data logging and control are possible.

2. MATHEMATICAL MODELING

Theoretical research undertaken at our Division concentrated on the fields of:

- preliminary design studies of new units using advanced clean coal technology [17], [18], [19], [20], [22], [27], [28],
- strategy of modernization of existing units [12], [24],
- steady-state analysis of various plant configurations [12], [16], [21], [26], [31], [33],
- simulation of off-design and part loading operation [11], [15], [25], [26], [32],
- developing the methods of modeling and simulation of unit operation under transient conditions [1], [3], [4], [6], [7], [8], [9], [10], [13], [14], [34], [35], [36].

The last one of these topics aroused our highest interest. The research on unit's transient operation was preceded by detailed studies of its design and off-design operation. Generally, commonly used models applied the lumped--parameter systems for describing the transient unit performance. As an example of such application our study of PFBC CC power plant is presented. Fig. 3 shows the components of the system. Each part of the unit can be described using the set of nonlinear differential equations representing laws of mass and energy conservation. In the models using lumped-parameter systems compressor and turbine performance is usually represented by non-dimensional steady--state characteristics. More information about the used models and results of our research were presented in [1], [2], [3], [4], [10], [13].

The more advanced models used distributed-parameter systems. The fast development of computer hardware and numerical methods significantly increased the possibility of solving complicated problems, however the solution of the non-steady process in three dimensional geometry is still impossible to obtain. Intensive research has been undertaken on application of distributed-parameter system, using one-dimensional models. As an example the simulation of power gas turbine rapid shutdown is presented. Fig. 4 shows the comparison of simulation results of dynamic operating behavior of gas turbine obtained using models with lumped- and distributed-parameter systems. Temperature distribution across gas turbine flow path is presented below in Fig. 5. Papers [14], [34], [35], [36] provide more detailed information.

Several series of experiments using PFBC stand is planned to verify the created models.

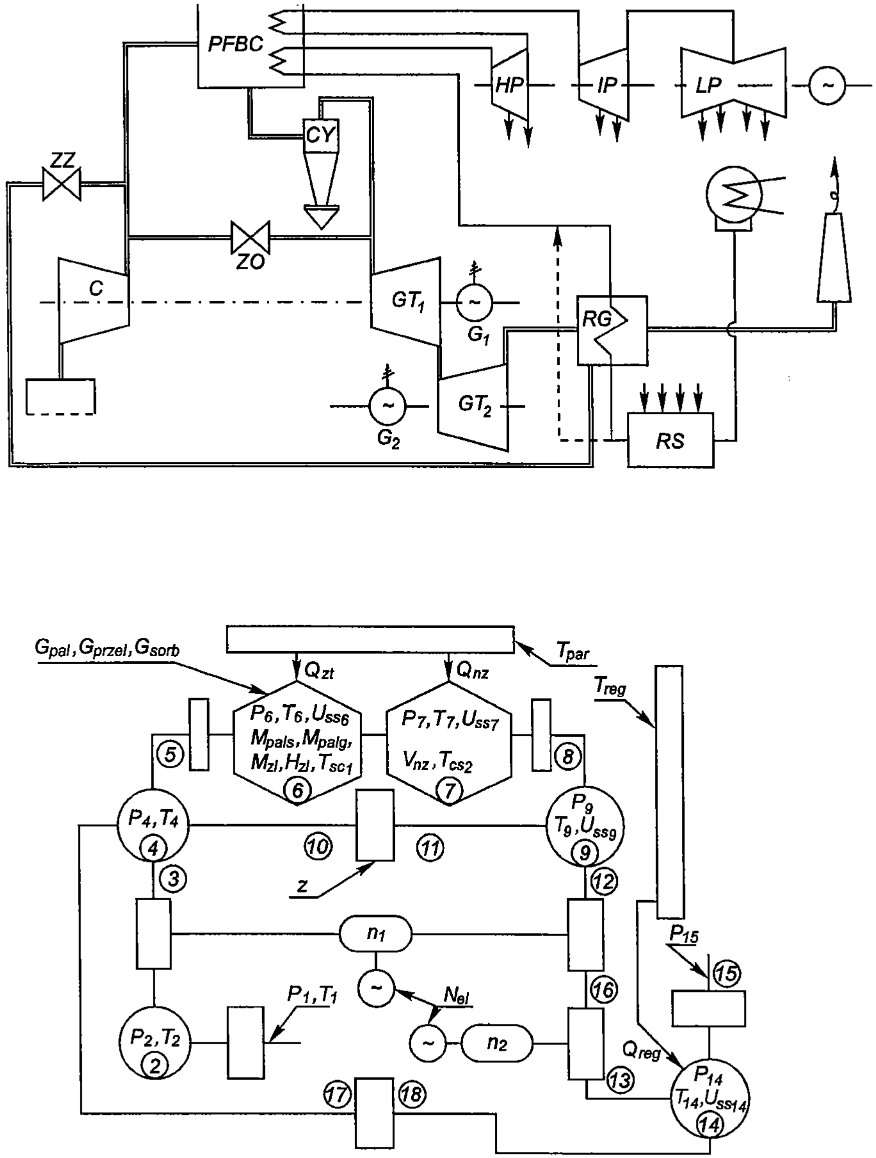

Fig. 3. Model PFBC installation scheme (top): C – compressor, GT_1, GT_2 – parts of gas turbine, G_1, G_2 – generators, PFBC – pressurized fluidized bed boiler, HP, IP, LP – high pressure, intermediate pressure, low pressure parts of steam turbine, RG – regeneration system supplied from gas cycle, RS – regeneration heaters system supplied from steam cycle, CY – cyclone, ZZ, ZO – by-pass valves. Schematic structure of mathematical model (bottom): p – pressure, T – temperature, u_{ss} – components of flue gases, M_{pals} – burned fuel, M_{palg} – mass of gasified fuel, H_{zl} – fluidized bed height, M_{zl} – mass of fluidized bed, T_{par} – outlet steam temperature, T_{reg} – feedwater temperature before regeneration heaters system, Q_{reg} – heat exchanged in regeneration system, N_{el} – electric power, n_1, n_2 – gas turbine rotors revolution, G_{pal} – unburned coke mass flow, G_{przel} – overflow mass flow, G_{sorb} – sorbent mass flow, Q_{zt} – heat exchanged in the fluidized bed, Q_{nz} – heat exchanged in overbed zone, V_{nz} – fluidized bed volume, T_{sc} – wall temperature

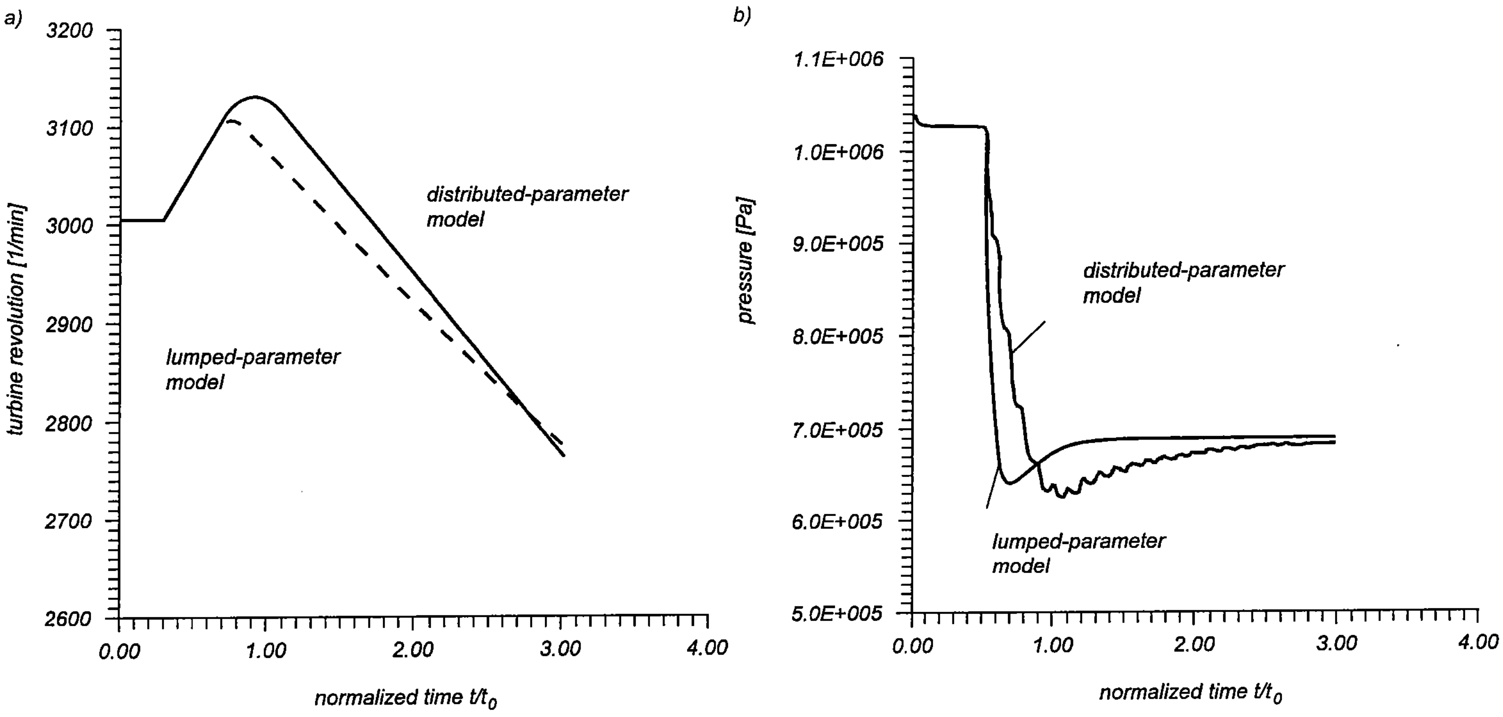

Fig. 4. Results of gas turbine rapid shutdown simulation obtained using models with distributed- and lumped-parameter systems: a) turbine revolution vs normalized time, b) pressure after combustion chamber vs normalized time

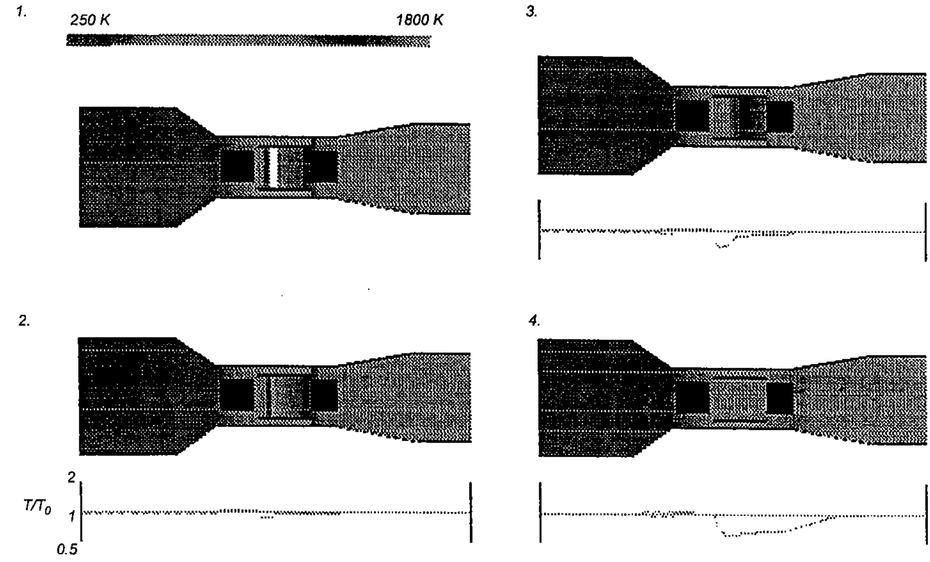

Fig. 5. Gas turbine temperature distribution during simulated process of rapid shutdown. Figures *1*, *2*, *3*, *4* present results of the simulation appropriately at 0, 0.5, 1, 2 s of process duration. The temperature scale is presented above the first figure. Actual to initial T/T_0 temperature ratio is given below figures *2* to *4*

CONCLUSIONS

At our Division the unique PFBC experimental installation was created. It can be used for further investigation under development of PFBC technology, verification of theoretical research and even preliminary operators training before the start of commercial operation of such type of plant. Results obtained thanks to theoretical and experimental research may certainly improve possibility of implementation of advanced clean coal technologies in Poland.

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TEORETYCZNE I EKSPERYMENTALNE BADANIA NAD CZYSTYMI TECHNOLOGIAMI WĘGLOWYMI, PROWADZONE W ZAKŁADZIE MASZYN I URZĄDZEŃ ENERGETYCZNYCH INSTYTUTU TECHNIKI CIEPLNEJ – STANOWISKO DOŚWIADCZALNE PFBC

Streszczenie

W pracy przedstawiono ostatnie wyniki badań nad czystymi technologiami energetycznego wykorzystania węgla, przeprowadzonymi w Zakładzie Maszyn i Urządzeń Energetycznych Instytutu Techniki Cieplnej.

Zamieszczono szczegółowe informacje o unikatowym stanowisku z doświadczalnym ciśnieniowym kotłem fluidalnym (PFBC) o mocy 3 MW_{th}.

ТЕОРЕТИЧЕСКИЕ И ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ЧИСТЫХ УГОЛЬНЫХ ТЕХНОЛОГИЙ, ПРОВОДИМЫЕ НА КАФЕДРЕ ЭНЕРГЕТИЧЕСКИХ МАШИН И ОБОРУДОВАНИЯ ИНСТИТУТА ТЕПЛОТЕХНИКИ – ИСПЫТАТЕЛЬНЫЙ СТЕНД PFBC

Краткое содержание

В работе представлены новейшие результаты исследований чистых технологий энергетического потребления угля. Исследования были проведены на Кафедре энергетических машин и оборудования Института теплотехники.

Приведены подробные информации об экспериментальном испытательном стенде с исследуемым флюидальным котлом, работающим под давлением (PFBC), тепловой мощностью в 3 МВт.