THE APPLICATION OF AN EXPANSION TURBINE IN THE PRODUCTION OF EXPANDED AGGREGATES

Tomáš Hlinčík, Karel Ciahotný, Petr Buryan

Department of Gaseous and Solid Fuels and Air Protection, University of Chemistry and Technology Prague, Technická 5, 166 28, Prague, Czech Republic, e-mail: tomas.hlincik@vscht.cz

The research into the expansion of Cypris clay from the overburden rocks of the Družba brown coal open-pit mine in North Bohemia has proven that targeted expansion enables good use of the thermal energy of hot aggregates, which has not yet been fully exploited. The integration of an electricity production expansion turbine into the production line and the use of residual gas heat in the turbine cycle can reduce production costs. The article assesses two possible solutions for the integration of the expansion turbine into the technological line, namely with an open and closed working cycle using various gaseous media. In both cases, the proportion of the energy usable for electricity generation in the expansion turbine cycle has been calculated along with the possible fuel savings in the rotary kiln by using combustion air preheated to a high temperature by the residual heat of the gas from the turbine gas cycle.

Keywords: Cypris clay; expansion; turbine; waste heat

Submitted 17. 08. 2020, accepted 15. 10. 2020

1. Introduction

Expanded aggregates are mainly produced from Cypris claystones. Because of their origin, these materials usually contain a significant admixture of bitumen and combustible organic substances. Major sources of Cypris claystones in the Czech Republic can be found in the Sokolov Cypris Formation, which consists of three strata. The upper layers of the sediment formation comprise light, porous, light-greenish and grey claystones and clays, containing kieselguhr. These sediments can be as much as ten metres thick [1, 2]. The middle layer is the best for the production of light, expanded construction and insulating ceramic material [3]. The upper stratum is mostly unusable, and the understratum is suitable for the production of brick goods.

For the clay to be utilisable for the production of expanded building materials by bloating in the heat, it must meet a number of conditions [3, 4]. Upon reaching pyroplastic temperature, at which the bloating process begins, the starting material should have a small pore volume and a dense structure. In addition, the raw material must contain such a mixture of fluxes (a mixture of CaO, MgO, iron oxides and alkali) that retains the released gases precisely at the time when the pyroplastic state involving surface sintering is reached. The influence of the chemical composition of clay materials on their viscosity and expansion properties have been summarised by Riley [5]. He claims that for optimal expansion, it is necessary to create a flux of suitable viscosity and surface tension at temperatures around 1,000 °C. He made a triangular diagram with the components SiO_2, Al_2O_3 and a group of oxides (MgO, CaO, FeO, Fe_2O_3, Na_2O, K_2O), in which he marked the boundaries between the areas of expanding and non-expanding clays. Based on Riley, the following concentration ranges are the most favourable for the formation of the pyroplastic state: 55 – 78 wt. % of SiO_2, 12–25 wt. % of Al_2O_3, with the sum of flux concentrations being 8 – 25 wt. %. These boundaries were later modified by Wilson [6].

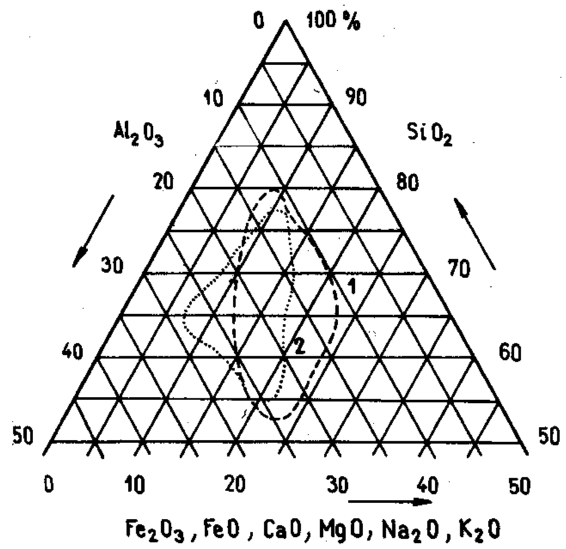

Fig. 1 Chemical composition of clays suitable for expansion [5, 6]
1 – the area according to Riley,
2 – the area according to Wilson

It is currently stated in a number of studies that the complex character of the expansion process prevents the application of the generally valid relations between the expansion ability and the data acquired through chemical, spectral, petrographic or thermal analyses [7-9] because each raw material has its specific properties, as a result of which it must be assessed individually. The content of alkaline earths should reach 3 – 6 wt. % and the content of iron oxides 6 – 10 wt. % [3]. Nevertheless, the melting point must never be decreased by the presence of fluxes to such an extent that it would lead to the creation of thin melt releasing gas outside the granules. An excess of CaO or Fe_2O_3 undesirably reduces the interval between sintering and melting temperatures [10]. The content of CaO needs to be adjusted in order to achieve suitable expansion in the range of 50 – 100°C [3].

The presence of organic substances in the expanded raw material is necessary because the products of their thermolysis facilitate the expansion process [9]. Their excess (over 3 wt. %), however, causes a high degree of the sharpening of the raw material, which is undesirable [10]. Through the rapid burning of the organic substances at the rotary-kiln inlet at high temperatures, clay granules disintegrate. If the raw clay contains the desirable amount of organic substances, it is not necessary to support the expansion by adding more organic substances. Besides apparent density, the quality of expanded materials is also defined by their strength, which mainly depends on porosity and the related pore-wall thickness. Quality industrial products have small, asymmetrical and homogeneously distributed pores. On the other hand, products of poor quality are light, fragile or heavy. Light products have fewer but larger pores; consequently, their thin walls cannot provide the desired strength. Heavy products have a strong central zone with relatively small pores and an outer zone with interconnected large pores.

The average chemical composition of the claystones from the Cypris formation in the Sokolov Basin is shown in Table 1.

Tab. 1 The average chemical composition of Cypris clay [11]

Oxide	Content (wt. %)
SiO_2	38.75
Al_2O_3	22.60
Fe_2O_3	9.38
TiO_2	3.15
CaO	3.14
MgO	2.16
K_2O	2.00
SO_3	0.51
Na_2O	0.35

The industrial process of the production of light aggregates from expanded clay varies according to the characteristics of the input material. It depends on water content and the composition of natural materials. It uses a procedure involving crushing or grinding and subsequent granulation. The firing and expansion take place in rotary kilns at temperatures of 1,100–1,150 °C [12]. Rotary kilns are heated directly in the opposite direction by natural gas or brown-coal multi-dust. The technological process involves the production of a wide fraction and subsequent sorting into narrow fractions.

The technological process consists of the following main steps. Raw clay is crushed and plasticised in several stages. Subsequently, granules of the necessary size are created, after which they enter the rotary kiln. The water content in the granules ranges from 18 to 20 %. If the granules are sufficiently plastic and homogenised to maintain their shape without disintegration into small parts, the lower water content is not a problem [13].

The clay enters the rotary kiln; the temperature at its beginning ranges between 250 and 350 °C and it gradually increases along the length of the kiln. The increase in temperature is not uniform. In the first 12 – 13 minutes of heating, free water evaporates. In the subsequent part of the rotary kiln, after drying, the temperature rises; and in the pyroplastic state of the heated material, thermolysis of organic substances is applied here. In the final part of the kiln, the fired clay is cooled [14].

After the release of CO_2 from the decomposition of carbonates and after the burnout of organic substances, the surface of the fired clay is oxidised at temperatures higher than 700 °C. For the expansion process, this oxidation is necessary. The iron present passes to a higher valence state; with the silicate base, it forms complexes with a higher melting temperature. To ensure the oxidation environment, combustion is carried out with an excess of air. Inside the heated granules, a reducing environment is maintained through the presence of organic substances. In it, ferrous oxide can be retained even at higher temperatures.

At temperatures around 1,000 °C, gas is produced inside the granule, causing the grain to expand [15, 16]. At this stage, the quality of the surface oxidation is important – the surface must withstand the temperature needed for expansion without melting, otherwise the entire heated layer of the raw material would be sintered. The expansion requires not only the formation of mixtures with low melting temperature but also gas formation and release at the time of the formation of the pyroplastic state of the granule. These conditions are created by the presence of iron compounds and the reduction environment inside the grain. The temperatures of the expansion of Cypris clay at which the product of the necessary weight and quality is to be produced are mainly dependent on the chemical composition of the raw material, which affects meltability and the formation of the pyroplastic state [17].

The finished product proceeds from the kiln to a rotary cooler, through which it passes for approximately 15 – 25 minutes, being cooled below 80 °C. The cooled granulate is transported to a sorter, where it is sorted into individual fractions. The sorted product is stored in closed silos or in open landfills. A part of it is further processed by crushing. The technological scheme of production is shown in Figure 2.

1.1. The use of an expansion turbine in the production process

The expanded materials are produced in a rotary kiln. From the kiln, the product is carried to a drum cooler, in which it is cooled by countercurrent air. In this technological node, it would be possible to place a cogeneration system that would use the waste heat released from the product during its cooling and would convert it using an expansion gas turbine into electricity.

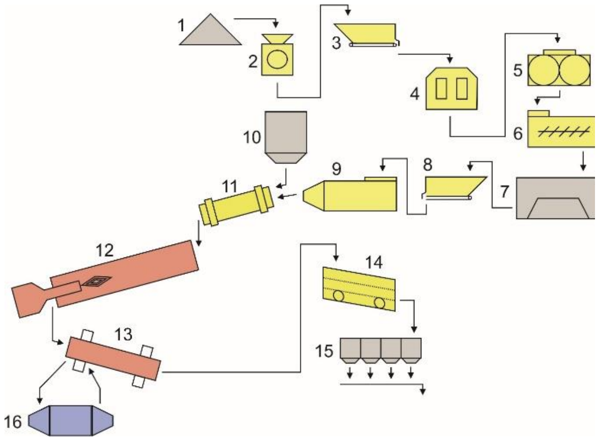

Fig. 2 Production scheme
1– feedstock, 2 – hammer crusher, 3 – box feeder, 4 – swing-hammer mill, 5 – pre-grinding roller mill, 6 – trough mixer, 7 – storage of the processed feedstock, 8 – box feeder, 9 – forming press, 10 – container with an additive, 11 – powder drum, 12 – rotary kiln, 13 – heat exchanger + drum cooler, 14 – sorter, 15 – silos, 16 – expansion turbo set

For the use of waste heat by means of an expansion turbine, two basic principles of the cogeneration system are applied in external combustion processes now [18]:

- An open-cycle cogeneration system – an indirectly fired gas turbine (IFGT) – Fig. 3.
- A closed-cycle cogeneration system – an externally fired gas turbine (EFGT) – Fig. 4.

In the case of the IFGT, the system is always entered by a new gaseous medium, mostly air, which is heated by flue gases and subsequently expands in the expansion turbine. The EFGT system is more efficient than the IFGT, but its disadvantages include its higher material demands and overall higher investment costs [19, 20]. The systems are schematically depicted in following figures.

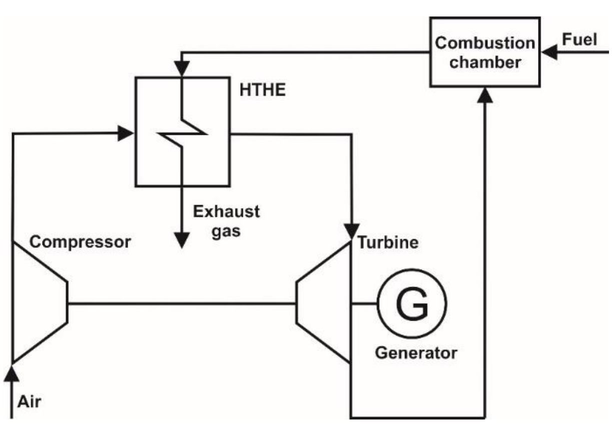

Fig. 3 A scheme of an open-cycle indirectly fired expansion turbine [21]

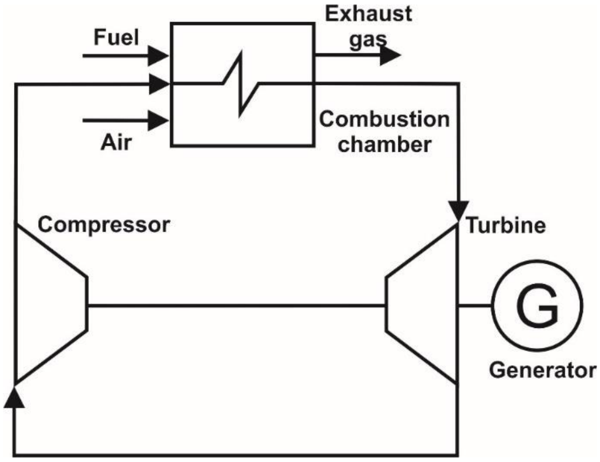

Fig. 4 A scheme of a closed-cycle externally fired expansion turbine [19]

In the first case, the variant of the open-cycle expansion turbine (IFGT) was evaluated. In this arrangement, only air can realistically be used as an expansion medium. Since the air coming out of the expansion turbine still has a high temperature and carries a large amount of thermal energy, this air was planned to be used as combustion air in the burner of the rotary kiln. For this arrangement of the technological process, the fuel savings per tonne of the produced aggregate were calculated.

In the latter case, the use of the closed-cycle expansion turbine (EFGT) in which the high-temperature heat exchanger (HTHE) is placed in a drum cooler was evaluated – see Figure 4. For this system, various working media were tested. The possibility of using the residual heat of the expansion gas leaving the gas turbine to preheat the combustion air was again assessed. In this case, it was necessary to include a heat exchanger in the gas cycle of the expansion turbine. Its effectiveness was selected at 80%. Under the given conditions, the fuel savings in the rotary kiln were again calculated in the same way as in the previous case.

All calculations worked with the temperature of the product entering the heat exchanger being 1,100 °C, the exit temperature of the product being 100 °C and the exit temperature of the gaseous medium being 900 °C. The temperature of the gaseous medium entering the heat exchanger varied, depending on the specific gas used in the gas cycle of the expansion turbine. Before entering the heat exchanger, this gas was compressed to a pressure of 250 kPa, which caused the heating of the gas to temperatures mostly exceeding 100 °C.

2. Experimental

Model calculations were performed using Aspen HYSYS version 8.8. The following figure shows the scheme for model calculations. A property package based on the Peng-Robinson state equation was chosen for the calculation:

$$P = \frac{RT}{V_m - b} - \frac{\alpha}{V_m^2 + 2abV_m - b^2}, \qquad (1)$$

$$a = \frac{0.45724R^2T_c^{2.5}}{P_c}, \quad (2)$$

$$b = \frac{0.07780RT_c}{P_c}, \quad (3)$$

$$\alpha = \{1 + (0.37464 + 1.5422\omega - 0.26992\omega^2)(1 - T_r^{0.5})\}^2, \quad (4)$$

where P is pressure, V_m molar volume, R universal gas constant, T thermodynamic temperature, P_c critical pressure, T_c absolute critical temperature, and ω acentric factor.

The model of a closed-cycle externally fired expansion turbine included four essential components:

- compressor,
- heat exchanger,
- expansion turbine,
- cooler.

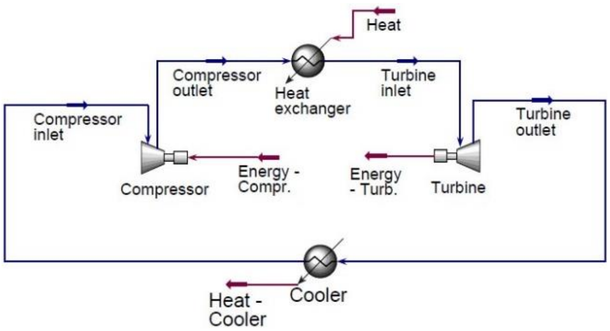

Fig. 5 A scheme of a closed-cycle externally fired expansion turbine for model calculations

A centrifugal compressor was chosen for the calculation. The total adiabatic efficiency for both the turbine and the compressor was selected at 75 %.

The gaseous medium enters the compressor at the temperature of 15 °C and the pressure of 101 kPa. In the compressor, the gaseous medium is adiabatically compressed to a pressure of 250 kPa. Consequently, its temperature increases. The gaseous medium is then led to the heat exchanger, which simulates the heat exchanger located in the drum cooler (see Figure 2). The gaseous medium is heated here to 900 °C. During the heating, the pressure is considered to be constant (isobaric heating). The medium leaving the heat exchanger is further led to the expansion gas turbine. Here, as a result of the expansion of the gaseous medium, the flowing medium is cooled as well. From the expansion turbine, the gaseous medium is fed in the case of the open cycle (IFGT) to the burner of the rotary kiln, in the case of a closed cycle (EFGT) to a heat exchanger, where it is cooled by combustion air to 15 °C. The efficiency of this indirect heat exchanger was selected at 80 %.

3. Results and discussion

The aim of the model calculations was to assess possible energy savings by using the residual heat of the ceramic material leaving the rotary kiln. This heat can be utilised to generate electricity using an expansion gas turbine and also to heat combustion air for the rotary kiln. The difference between the energy supplied to the compressor and the energy produced in the expansion turbine using various gaseous media was calculated in each of the proposed solution variants (the open and closed gas cycle with an expansion turbine). Another goal was to calculate the amount of energy that can be obtained when the gas is cooled to its original temperature of 15 °C before it enters the compressor.

The following gases were selected for the simulation calculations:

- air,
- carbon dioxide,
- nitrogen,
- helium,
- argon.

For model calculations, a constant molar flow rate of 100 kmol h^{-1} was first selected for all model gaseous media. The cooling rates will vary depending on the specific heat capacities of the gaseous media. The results of the calculations are given in Table 2. Table 3 then shows the differences between the energy obtained from the turbine and the energy supplied to the compressor.

Tab. 2 The results of the model calculations using different types of gaseous media

Gas	Compressor outlet temperature (°C)	Turbine outlet temperature (°C)	Heat for heating to 900 °C (kWh/100 kmol)	Heat obtained from the cooler (kWh/100 kmol)	Energy supplied to the compressor (kWh/100 kmol)	Energy obtained from the turbine (kWh/100 kmol)
Air	129.4	722.1	676.8	603.7	91.9	164.9
Carbon dioxide	96.7	788.0	1106.0	1022.0	88.2	172.3
Nitrogen	127.4	720.1	678.0	605.0	91.7	164.7
Helium	182.8	632.6	414.4	356.8	96.9	154.5
Argon	182.8	632.7	414.6	356.9	96.9	154.6

Tab. 3 Results of model calculations – the difference between the energy obtained and supplied

Gas	Energy difference (kWh/100 kmol)
Air	73.0
Carbon dioxide	84.1
Nitrogen	73.0
Helium	57.6
Argon	57.7

Nevertheless, the individual model gases used for the comparison have different heat capacity. The cooling of the expanded aggregate to the same temperature will require different rates of the gas flow through the cooling cycle depending on the respective central value of the heat capacity of the particular gases.

The specific heat capacity of the selected model gases, their heat-exchanger inlet and outlet temperatures and the average heat-capacity values for the temperature intervals studied are given in Table 4.

Tab. 4 The temperatures and the specific heat-capacity values of the selected expansion gases

Gas	Gas temperatures			Specific heat capacity of the gas		
	Turbine inlet temperature (°C)	Turbine outlet temperature (°C)	Temperature difference (°C)	Turbine inlet (kJ kg^{-1} °C^{-1})	Turbine outlet (kJ kg^{-1} °C^{-1})	Average value (kJ kg^{-1} °C^{-1})
Air	900	722.1	177.9	1.170	1.135	1.153
Carbon dioxide	900	788.0	112.0	1.274	1.243	1.259
Nitrogen	900	720.1	179.9	1.189	1.162	1.176
Helium	900	632.6	267.4	5.196	5.196	5.196
Argon	900	632.7	267.3	0.521	0.521	0.521

In terms of heat capacity, the most suitable expansion gas seems to be helium, which has approximately five times higher heat capacity than the other selected model gases. This means that when it is used, the cooling of the ceramic material to the same final temperature will require approximately a five times lower gas mass flow rate than in all the other cases except for argon. In all the cases, however, the gas will flow in a closed cycle, as a result of which its volume used can be similar in particular cases. Furthermore, it is evident from Table 4 that the individual heat capacities of the selected expansion gases are only little dependent on the temperature at the given temperature intervals relevant for their use in the expansion-turbine cycle.

In addition, the amount of the energy obtained in the expansion set from one tonne of the expanded aggregate cooled from 1,100 °C to 100 °C was estimated while ignoring heat losses to the environment. The specific heat capacity of the expanded ceramic material reported in the literature [22] is 1.26 kJ kg^{-1} K^{-1}. The cooling of one tonne of this material by 1,000 °C thus provides 1,260 MJ of heat. This heat can theoretically be used to heat expansion gas. The number of the moles of gas needed to dissipate this heat from the ceramic material cooler is given in Table 5, which also shows the amount of energy produced by the expansion turbo set when cooling 1 tonne of this material from 1,100 °C to 100 °C and the amount of the fuel saved in each of the cases studied.

Tab. 5 The amount of the expansion gas required to cool one tonne of ceramic material from 1,100 °C to 100 °C and the energy obtained in the expansion turbo set

Gas	The required amount of gas (kmol t^{-1})	Energy from the turbo set per 1 t of material (kWh t^{-1})	Fuel savings in the rot. kiln (kWh t^{-1})	Total energy obtained (kWh t^{-1})
Air – IFGT	670	−489	−4,046	−4,535
Air – EFGT	670	−489	−3,237	−3,726
Carbon dioxide	410	−345	−3,353	−3,698
Nitrogen	669	−488	−3,238	−3,726
Helium	1,095	−630	−3,124	−3,755
Argon	1,094	−632	−3,124	−3,755

The table shows that individual working gases used in a closed cycle provide very similar energy savings. The highest amount of the residual heat of ceramic materials for the production of electricity is used in the case of rare gases and the lowest in the case of carbon dioxide. The open working cycle with air provides higher possible energy gains than closed cycles because combustion air leaving the gas turbine can be used directly in the rotary-kiln burner, whereas in the case of a closed working cycle, this air passes through a heat exchanger, in which the heat-transfer efficiency has been calculated to be only 80 %.

4. Conclusion

The article is aimed at evaluating the possibilities of using waste heat from the cooling of the expanded aggregate leaving the rotary kiln (at temperatures of 1,000 –1,150 °C) to generate electricity through an expansion turbine and of utilising the residual heat to heat the combustion air for the rotary kiln. Computational models of an open-cycle indirectly fired expansion turbine and a closed-cycle externally fired expansion turbine have been made based on these assumptions. Non-explosive, inert gases were selected in the individual compared variants of the possible solution. In the closed cycle studied, the most advantageous heating gaseous media are the inert gases helium and argon. When these gases were used, the energy gain in the form of the electricity produced was calculated at 630 kWh t^{-1} of the cooled ceramic material. When air was used, the amount of the electricity generated was 489 kWh t^{-1}.

Nevertheless, a much greater economic profit can be achieved by using the residual heat of the expansion gas for heating the combustion air used in the rotary kiln. In individual cases, possible fuel savings vary from 3,124 kWh t^{-1} (using Ar or He) to 3,353 kWh t^{-1} (in the case of CO_2).

When air is used as an expansion gas in the working cycle of the turbine, the calculated fuel savings in a closed cycle are 3,237 kWh t^{-1} and in the case of an open cycle 4,046 kWh t^{-1} of the cooled aggregate.

It is clear from the results obtained that the use of the rather complex expansion turbine system for the generation of electricity from the residual heat of the ceramic material is not an optimal solution. A better option is to use the residual heat of the ceramic material to heat the combustion air for the rotary kiln and to use the saved amount of fuel to generate electricity and heat in the classic cogeneration unit. Both of these systems have been verified many times in technical practice and belong to the standard technology in the field concerned.

Refenrences

1. Kříbek B., Knésl I., Rojík P., Sýkorová I., Martínek K.: Geochemical history of a Lower Miocene lake, the Cypris Formation, Sokolov Basin, Czech Republic. J. Paleolimnol, **2017**, 58 (2), 169-190.
2. Kříbek B., Strnad M., Boháček Z., Sýkorová I., Čejka J., Sobalík Z.: Geochemistry of Miocene lacustrine sediments from the Sokolov Coal Basin (Czech Republic). Int. J. Coal. Geol., **1998**, 37 (3-4), 207-233.
3. Buryan P.: Gas generation during Cypris clay expansion. J. Therm. Anal. Calorim., **2018**, 134(2), 981-992.
4. Dondi M., et al.: Lightweight aggregates from waste materials: Reappraisal of expansion behavior and prediction schemes for bloating. Constr. Build. Mater., **2016**, 127, 394-409.
5. Riley C.M.: Relation of Chemical Properties to the Bloating of Clays. J. Am. Ceram. Soc., **1951**, 34(4), 121-128.
6. Wilson H.: Lightweight aggregates for the construction industry. Journal of the Canadian Ceramics Society, **1951**, 22, 44-48.
7. Gerasimov V.V., Porfireva R.T., Gabidullin, M.G.: Modifying additive to raw mixture for keramzit production. Glass and Ceramics, **1993**, 50, 48-50.
8. Ivleva I.A., Shimanskaya M.S., Nemets I.I.: Technology for producing keramzit from low expandable clay. Glass and Ceramics, **2012**, 68(11-12), 363-365.
9. Ozguven A., Gunduz L.: Examination of effective parameters for the production of expanded clay aggregate. Cement Concrete Comp., **2012**, 34(6), 781-787.
10. Decleer J., Viaene W.: Rupelian Boom clay as raw material for expanded clay manufacturing. Applied Clay Science, **1993**, 8(2-3), 111-128.
11. Buryan P.: Kapalné produkty bitumenu cyprisových jílů. Paliva, **2010**, 12, 13-20.
12. Chen H.J., Yang M.D., Tang C.W., Wang S.Y.: Producing synthetic lightweight aggregates from reservoir sediments. Constr. Build. Mater., **2012**, 28(1), 387-394.
13. Kuneš P.: Keramzit a jeho aplikace. Stavební obzor, **1993**, 4, 104-108.
14. González-Corrochano B., Alonso-Azcárate J., Rodas M.: Effect of prefiring and firing dwell times on the properties of artificial lightweight aggregates. Constr. Build. Mater., **2014**, 53, 91-101.
15. Chopra S.K., Lal K., Ramachandran V.S. Gas-producing agents in the production of lightweight aggregates. Journal of Applied Chemistry, **2007**, 14(5), 181-185.
16. Lee KG.: Bloating Mechanism of Lightweight Aggregate with the Size. J. Korean Ceram. Soc., **2016**, 53(2), 241-245.
17. Ehlers E.G.: The mechanism of lightweight aggregate formation. The American Ceramic Society Bulletin, **1958**, 2, 95-99.
18. Datta A., Ganguly R., Sarkar L.: Energy and exergy analyses of an externally fired gas turbine (EFGT) cycle integrated with biomass gasifier for distributed power generation. Energy, **2010**, 35(1), 341-350.
19. Al-attab K.A., Zainal Z.A.: Externally fired gas turbine technology: A review. Appl. Energ., **2015**, 138, 474-487.
20. Soltani S., Mahmoudi S.M.S., Yari M., Rosen M.A.: Thermodynamic analyses of an externally fired gas turbine combined cycle integrated with a biomass gasification plant. Energ. Convers. Manage., **2013**, 70, 107-115.
21. Kautz M., Hansen U.: The externally-fired gas-turbine (EFGT-Cycle) for decentralized use of biomass. Appl. Energ., **2007**, 84 (7-8), 795-805.
22. Pániková J.: New additional insulation systems for higher temperatures. Bachelor's thesis, **2013**, Brno University of Technology.