Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 57 (2014) 2305– 2314

Energy Procedia

2013 ISES Solar World Congress

A set-up for an experimental verification of a new conception of solar powered house

Magdalena Nemś[a]*, Jacek Kasperski[a]

[a]Wrocław University of Technology, Wyb.Wyspianskiego 27, 50-370Wrocław, Poland

Abstract

A novel concept of energy self-sufficient house has been the main objective of theoretical research conducted by the authors of the paper. In general, a system is based on the collaboration of a large solar concentrating collector with a stone deposit accumulator fill with crushed granite. Air, as the working medium heated in the collector, is later sent to the deposit accumulator or directly to living space. Not only it is possible to heat living space by warm air or to cool it by the absorption system but also it is possible to produce electricity through the system to Organic Rankine Cycle or Peltier cells. Previous calculations confirmed the possibility of the year-round operation of the concept system in Polish climatic conditions. The next verification step is to carry out tests on an experimental set-up.

Selection and/or peer-review under responsibility of ISES.

Keywords: solar space heating system; heat storage system

3. Introduction

The world-going efforts are made in order to reduce the impact of the residential sector on the degradation of the environment. The choice of the heating system and the insulation thickness is no longer an individual matter. Currently, many countries and organizations such as the European Union have passed their laws and directives which regulate the issue of the energy-efficient building and recommend the use of systems based on renewable energy sources. Conventional technologies are slowly being replaced, for instance by solar plants operating in the summer. This process occurs also due to subsidies from the state budget, which have been introduced by many countries, including Poland.

Trend of ecobuilding also affects the development of the new solutions and innovations, which goal is to create the intelligent energy self-sufficient system. These issues usually are associated with the search

* Corresponding author. Tel.: +48-692-014-153; fax: +40-71-328-38-18.
E-mail address: magdalena.nems@pwr.wroc.pl.

Selection and/or peer-review under responsibility of ISES.
doi:10.1016/j.egypro.2014.10.238

Nomenclature

D_e	equivalent diameter, m
Pr	Prandtl number, -
Re	Reynolds number, -
T_{amb}	ambient temperature, ˚C
T_{in}	inlet temperature of the collector, ˚C
T_{out}	outlet temperature of the collector, ˚C
T_{air}	air temperature in the deposit, ˚C
T_b	temperature at the bottom of the deposit, ˚C
T_m	temperature in the middle of the deposit, ˚C
T_t	temperature at the top of the deposit, ˚C
ΔT_d	temperature rise in the deposit, ˚C
ΔT_c	temperature rise in the solar collector, ˚C
I_g	global radiation, W/m^2
I_b	beam radiation, W/m^2
I_s	scattered radiation, W/m^2
λ_{air}	thermal conductivity of air, W/m·K
α_{ow}	factor of heat transfer for the outer wall, $W/m^2 \cdot K$

for the possibly long-term accumulation of heat and electricity.

The authors of the article are working on the dedicated thermal system for a residential building. The concept is based on cooperation between solar collector and accumulator made from rocks. Previous works are described later in the section below.

4. The concept of the solar space heating system

The research subject matter is a single-family detached house built in Lower Silesia (Fig. 1) in Poland, equipped with a year-round solar thermal heating system. Wroclaw (the main reference city in this area) is located in moderate climate zones of north latitude. The average monthly air temperature in January is -1.1 ˚C, whereas in July it is 18.8 ˚C [1] (according to data for the period between the years 1961 and 2000).

The considered conceptual single-family building of approximately 180 m^2 of living area is built with the use of energy-efficient technology. Its demand for energy is 60 kWh/m^2. A scheme of a solar space heating system with a year-round rock bed dedicated for a single-family detached houses is presented in Fig. 2.

Fig. 1. Map of Europe, Poland with Lower Silesia region marked as the destination for the considered solar installation

The specificity of the heating system operation is as following: the concentrator can rotate to track and thereby receive direct solar radiation through the receiver. That receiver is used as an air heater. Air heated by the collector heats up the bed packed with stones and bricks. The choice of type of deposit was caused by its simplicity and, at the same time, desired cumulative properties. The heat transferred from the collector causes the packed bed to increase its temperature. The packed bed is thermally insulated with a thick layer of thermal insulation, thus its high temperature can be maintained even up to a few months. Once the living space requires heating, the space heating fan is activated, which through a system of space heating ducts transfers hot air from the packed bed into the living space. Active cooling of living space in summer time is also possible through the use of additional absorption or ejector device.

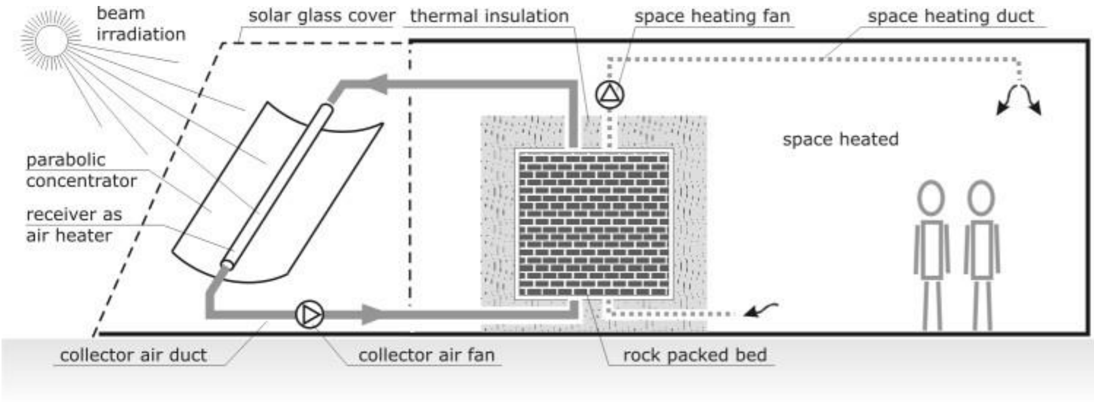

Fig. 2. Scheme of a solar space heating system with a year-round rock bed dedicated for a single-family detached house

As the projections suggested, the heating system would be capable of satisfying year-round heating requirements of the building, based mainly or solely on renewables. The operating principle of the system is relatively simple, however, it is large and heavy. According to the analyses carried out under Polish climate, a packed bed 3x3x3 m and a concentrator 8 m^2 in the surface area would be required. A collector, angled at 60 ˚, will be equipped with a uniaxial tracking system (tracker) to follow the Sun. After technical and economic analysis, as the filling material of the deposit granite ballast was chosen. It possesses good cumulative properties, it is cheap and easily accessible in Lower Silesia region. The deposit will be insulated with mineral wool.

The space behind a glass solar cover protects from wind. Using the parabolic collector is required to obtain high temperatures during winter, when solar radiation is low. It is aimed at ensuring a year-round operations of the conceptual heating system. Air has been chosen as working medium by reason of its prevalence and residents' safety in case of leakage in the system. Before delivering air into the heating system, it will be dehydrated. It will ensure long-lasting durability of the system and eliminate purchasing expensive structural parts, which is necessary in case of such media as, for instance, oil, glycol or water pressure system. A solar collector is also required to generate high temperatures, due to large amount of thermal energy necessary. The upper temperature limit is expected to be around 400 ˚C.

Preliminary numerical simulations [2] carried out for the climatic conditions of Wroclaw showed that the used system should operate in an annual cycle. The temperature of the deposit, even in winter, will not fall below 50 °C. The idea is that during this time the bed will be mainly discharged to provide the thermal comfort to home residents.

Polish Ministry of Transport, Building and Maritime Economy provides data of the typical meteorological year, prepared in accordance with EN ISO 15927:4 for 61 meteorological stations [3]. According to the data provided, during the winter in Wroclaw the average direct solar radiation on a horizontal surface is 125 W/m^2. The maximum value recorded for this interval is 380 W/m^2. The results of the calculations show that the radiation values allow for periodic recharging of the deposit, or direct heating of living areas by warm air from the collector.

5. An experimental set-up

As mentioned at the outset, the innovative concept presented above has to be tested on the real object. For this purpose the experimental set-up has been designed at a scale. The thermal performance has been adopted as the main criteria parameter. The set-up (Fig. 6) consists of a solar concentrating collector connected with a stone deposit accumulator.

5.1. The accumulation deposit

Designing a system requires an initial analysis of the heat exchange so as to select the optimal size of the deposit and the thickness of the thermal insulation. These issues must be taken into account in order to reduce heat losses to the environment and improve the heat accumulation process.

The size of the deposit was chosen so that it was impossible to complete its charge in up to a few days. This would allow to test the daily charging possibility of the bed throughout the year. Therefore, a calculation of the deposit size effect (m^3) per charging time (in hours) was done. The different temperature inside the deposit, the ambient temperature (0 ˚C), the average density of direct radiation (800 W/m^2) and the fill factor of the deposit (0.7) were obviously also taken into account.

Preliminary calculations are rough and do not include losses to the environment related to the thickness of the insulation and wind.

In the below chart (Fig. 3) the relationship between the volume of the deposit and the time of his charging is shown. For the purpose of the experiment, a proper size of an accumulator fill material will be 0.15 m^3. This size allows for free arrangement of the filling material. It will not be troublesome because of the containment structures. Estimated recharge time does not exceed a few days.

The selection of thermal insulation thickness was based on the analysis of heat loss from the deposit, according to Newton's law of heat exchange [4], as the heat flow through the system of flat walls to the surrounding area. The calculation of the accumulator was considered as a deposit dug from spheres, made of granite. As the characteristic dimension, instead of the sphere diameter, the equivalent diameter is introduced. In this case, it amounts to 0.05 m. The calculated flux of losses includes air temperature in the deposit, ambient temperature (assumed 0 ˚C), the diameter of the insulation, the thermal conductivity for mineral wool (0.035 W/m·K), and air speed (5 m/s) together with the equivalent diameter. Outer wall temperature was fixed at a higher level of 10 ˚C then ambient temperature - for safety reasons. This assumption has a negligible effect on the final results.

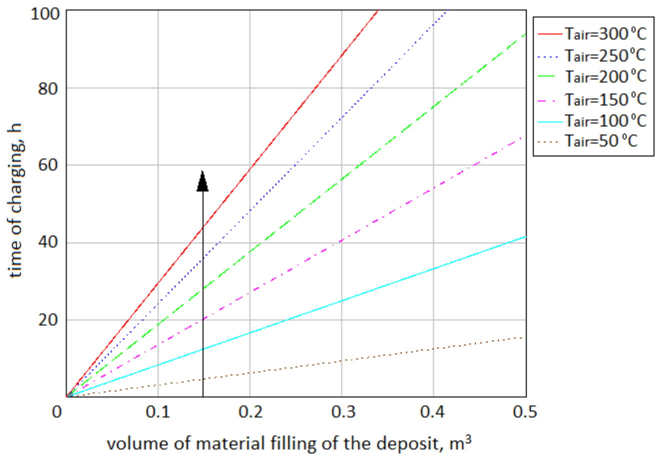

Fig. 3. Charging time for various volume of the accumulation deposit

Factor of heat transfer α_{ow} (1) for the outer wall (made of metal) was calculated from the Bec formula [5], which is used for deposits built up from ball elements:

$$\alpha_{ow} = 1.162(2) \cdot \frac{\lambda_{air}}{D_z} \cdot \left(0.203\,\mathrm{Re}^{1/3} \cdot \mathrm{Pr}^{1/3} + 0.22\,\mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.4}\right),\ \frac{W}{m^2 \cdot K} \qquad (1)$$

The result of the calculations was showed in Figure 4.

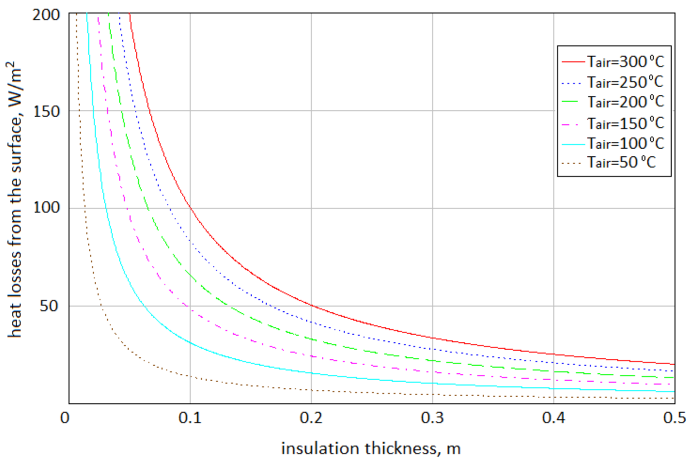

Fig.4. Heat losses in the deposit, depending on the thickness of the used insulation

Because of the relatively small heat loss, it seems that mineral wool with the thickness 0.3 m would be an optimal choice to insulate the concept house. Due to the increased flow of lifted heat losses, the insulation at the top of the deposit is 0.4 m. Under the bed, the insulation thickness is 0.2 m.

Rock packed bed in the moment of filling is shown in Figure 5.

Fig. 5. The deposit accumulation at the moment of filling

5.2. The concentrating solar collector

The tracker applied for the set-up preparation enables two axes of rotation (horizontal and vertical). The tracker made by a Polish producer, was equipped with a system, which automatically follows the brightest point on the sky. At night, the tracker was in a sleeping position, directed to the West. A concentrator with an aperture of 1.65 m^2 was prepared with the use of 2 cm wide strips made of glass mirror.

The typical purpose of the collector was to prepare hot water. Thus, a single evacuated probe shape absorber of 50 mm diameter was used. At the beginning, the absorber was applied as the air heater but because of to high temperature it cracked and imploded. Instead of the first one a new version of the absorber was built. A kind of pipe-in-pipe absorber was prepared, with air flowing into center pipe and returning flow in outer ring-shape area. The absorber was mounted into the probe-shape single glass evacuated envelope with a diameter of 44 mm.

A high-temperature resisting blower was designed and prepared in order to force the circulation of the heated air. Air from upper part of rock bed was directed through blower and next to the solar collector. Hot air exhausting from the solar collector was directed to lower part of the rock bed. The blower, rock bed and solar collector were connected with a duct system. To avoid the convective flow of hot air from upper part rock bed to the collector above, the electromechanical valve was mounted. The valve opened when blower was turned on, and closed when it was turned off. Due to the necessary tracker moves, flexible ducts, each of 1.5 m long, were mounted in order to connect the absorber and blower with the blower and valve. Finally, all parts of the system were thermally insulated.

5.3. Working principle of the set-up

On Figure 6 the schematically presented set-up and the real object were showed. The position is located at the Centre of Energy Technologies (CTE) in Świdnica near Wrocław.

The operating principle is as follows: a beam solar radiation is concentrated on the absorber and heats the working medium. Hot air is pumped by a fan into the bed accumulation. Then the air leaves the bed and is directed back into the collector. The system operates in a closed cycle. The running of the fan occurs when the temperature achieved in the absorber is higher than the temperature in the bed.

The system is equipped with a damper, which is closed when the system is not working. It prevents the convective movement of heat in the system and thus reduces flow losses from the deposit.

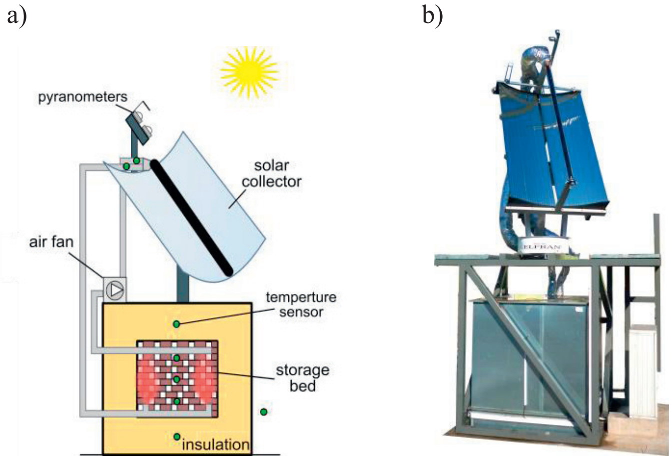

Fig. 6: a) Concept of set-up, b) the real object

Measuring apparatus in the form of temperature sensors (Pt 100) and two pyranometers has been marked in Figure 6. The measured parameters include: total and diffuse radiation, air temperature at the inlet and outlet of the collector, the temperature in the bed. The system does not have a power take-off.

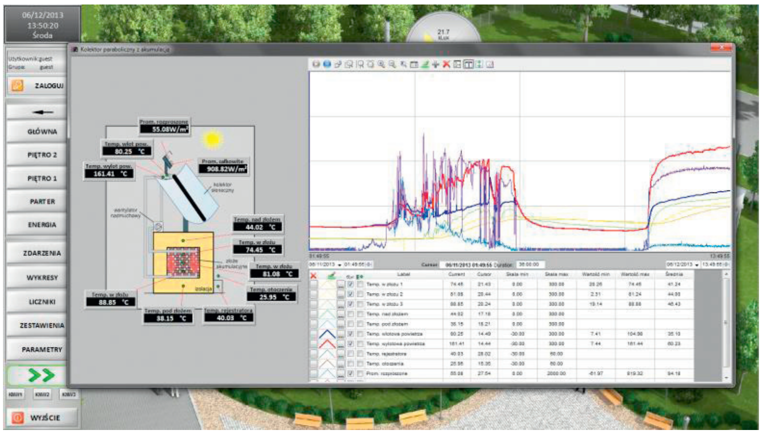

Fig.7. Building Management System

The data are read off every minute and stored on the DVR. The CTE building also has a Building Management System, which is used to control the operating parameters of all systems installed in the object. Due to this program it is possible to analyze the system on a regular basis, and download measurement data at any place that has Internet access.

6. Experimental studies

So far, preliminary tests of the system are carried out. The target launch and measurements on an annual cycle is planned for August 2013. The launch date is related to meteorological conditions prevailing at this time in Poland. Both ambient temperature and solar radiation should enable the use the full potential of the system.

Below, the results of daily research conducted from 15 to 17 May 2013 are presented. In Figure 8, the changes of total diffuse and direct radiation are shown. The maximum value of direct radiation was reached on May 16 at 11:49 and was 888 W/m^2.

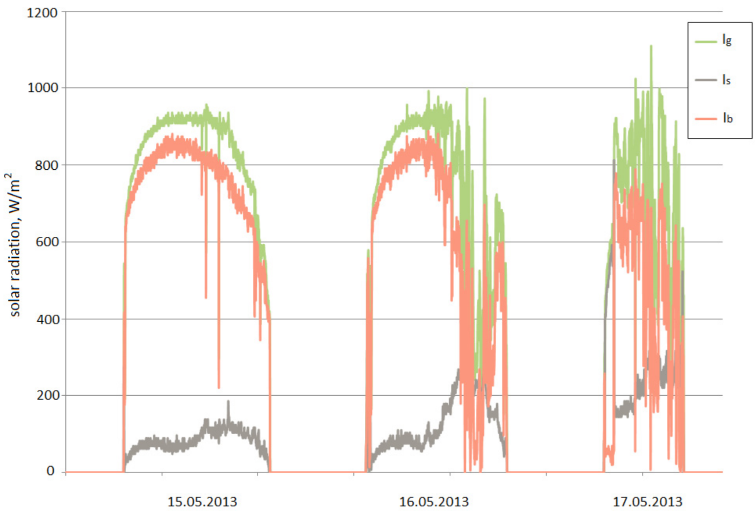

Fig. 8. Changes in the density of the solar radiation

Figure 9 shows changes in ambient temperature, temperature at the inlet and outlet of the collector, and temperatures in the upper, middle and lower part of the deposit accumulation. The highest temperature to which the air has been heated in the collector was 151.27 ˚C. However, deposit accumulation in those days was charged to a temperature of 79.13 ˚C.

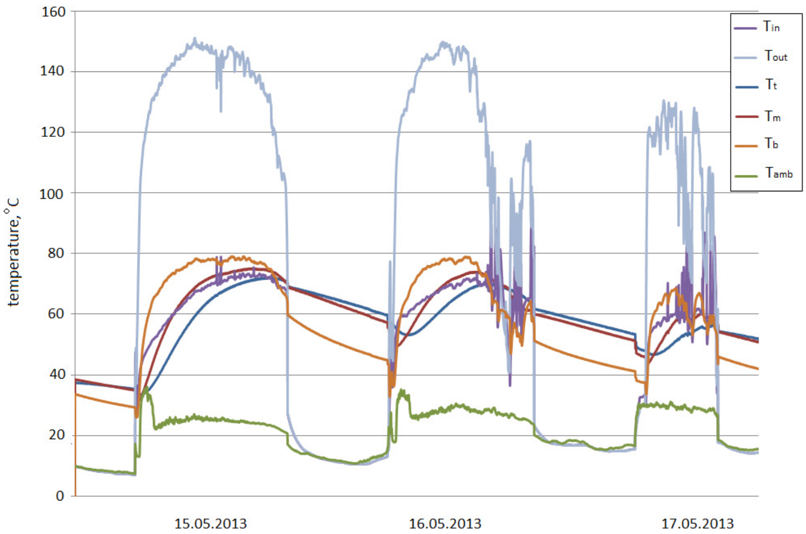

Fig. 9. Changes in temperature in the solar collector, deposit accumulation and ambient temperature

Figure 10 shows the temperature rise in the solar collector and deposit accumulation. During the night, temperature drops in the bed related to losses to the environment can be observed (Fig. 10). The lowering of the temperature in the bed is closely related to weather conditions such as ambient temperature, wind and precipitation.

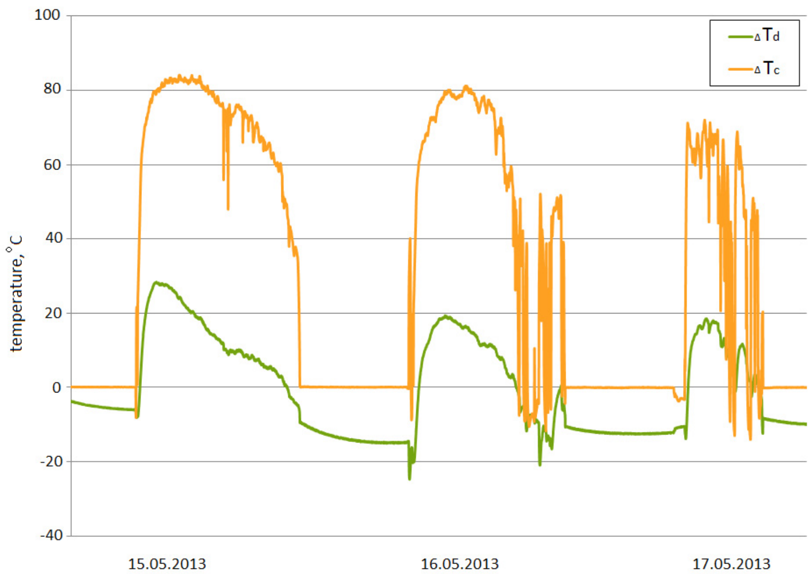

Fig. 10. The temperature rise in the bed and the solar collector

Additionally, using the differential pressure gauge, the pressure drop was measured which amounts to 1.8 kPa. On its basis the power loss was calculated which is 17.1 W. The pressure drop in the system is directly related to the previously stated (section 5.1) fill factor of the deposit.

In the same time final works are undertaken on the construction of the second set-up. It will serve to test the deposit accumulation in the laboratory conditions. It is planned to examine the influence of the fill factor, the influence of the filling elements size and their porosity on the efficiency of the process of accumulation.

7. Summary and conclusions

In the article the idea of the space heating system with a large linear concentrating solar collector combined with the granite accumulation deposit was presented.

The article also presents the way in which the experimental verification is performed, namely by means of drafting, building the set-up and long-term researches.

In August this year, tests on an annual cycle are planned to be run due to favorable meteorological conditions.

Appropriate scaling of the obtained parameters make the system perform a complete and realistic analysis of the possibility of heating the building during winter.

The detailed calculations determining the uptake of heat between particles of deposits and hot air will be the next step of work.

After the annual experiment, it is planned to create a full scale simulation of system that would work in a climate of Poland with a program such as TRNSYS.

Acknowledgements

Special thanks for The Centre of Energy Technologies in Świdnica, Poland.

References

[1] Department of Climatology, Jagiellonian University, Poland: www.klimat.geo.uj.edu.pl

[2] Nemś M., Kolasiński P., Kasperski J., *A solar high-temperature heat accumulation system with an ORC generator*, Proceedings of ISES Solar World Congress, August 28 - September 2, 2011, Kassel, Germany

[3] Polish Ministry of Transport, Building and Maritime Economy: www.transport.gov.pl

[4] Bejan A., Kraus A.D., Heat transfer handbook, 2003 by John Wiley & Sons, New Jersey

[5] Domański R., *Thermal energy storage handbook*, (in Polish) National Scientific Publishing House, Warsaw 1990