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COMPARATIVE EVALUATION OF THE PERFORMANCE OF A POLYMER SOLAR COLLECTOR

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Abstract.

Improving the energy efficiency of solar collectors, intensifying heat transfer processes, and optimizing their design parameters are pressing scientific and engineering challenges in autonomous heating and hot water supply systems. The relatively high mass, susceptibility to corrosion, and substantial heat losses in certain conventional flat-plate solar collector designs with metal absorbers create a need to develop alternative absorber designs based on polymer composite materials. This study presents a comparative analysis of the design, thermal performance, and economic indicators of a proposed flat-plate solar collector with a composite absorber based on a polymer matrix, aluminum powder, graphite, and Al_2O_3 nanoscale fillers against those of a conventional solar collector with a metal absorber. Preliminary theoretical calculations were used to assess the influence of composite composition on thermal conductivity and explore opportunities to improve the absorber's heat transfer characteristics and reduce heat losses. The capital and operating costs of the polymer solar collector, as well as the levelized cost of heat (LCOH), were also evaluated. The preliminary findings indicate that developing flat-plate solar collectors with polymer composite absorbers modified with metallic and nanoscale fillers is a promising approach to reducing structural mass, enhancing corrosion resistance, improving heat transfer characteristics, and achieving economic efficiency in autonomous heating and hot water supply systems.

Keywords

polymer solar collector, flat-plate solar collector, composite absorber, polymer matrix, aluminum powder, graphite, Al_2O_3, nanoscale filler, thermal conductivity, energy efficiency, exergy efficiency, LCOH.

Аннотация.

Повышение энергетической эффективности солнечных коллекторов, интенсификация процессов теплообмена и оптимизация их конструктивных параметров являются актуальными научно-техническими задачами автономных систем теплоснабжения и горячего водоснабжения. Относительно высокая масса, подверженность коррозии и значительные тепловые потери в отдельных конструкциях традиционных плоских солнечных коллекторов с металлическими абсорберами обусловливают необходимость разработки альтернативных конструкций абсорберов на основе полимерных композиционных материалов. В данном исследовании представлен сравнительный анализ конструктивных, теплотехнических и экономических показателей предлагаемого плоского солнечного коллектора с композиционным абсорбером на основе полимерной матрицы, алюминиевого порошка, графита и наноразмерных наполнителей Al_2O_3 и традиционного солнечного коллектора с металлическим абсорбером. На основе предварительных теоретических расчётов оценено влияние состава композиционного материала на его теплопроводность и изучены возможности улучшения теплообменных характеристик абсорбера и снижения тепловых потерь. Также оценены капитальные и эксплуатационные затраты полимерного солнечного коллектора и приведённая стоимость тепловой энергии (LCOH). Предварительные результаты показывают, что разработка плоских солнечных коллекторов с полимерными композиционными абсорберами, модифицированными металлическими и наноразмерными наполнителями, является перспективным направлением снижения массы конструкции, повышения коррозионной стойкости, улучшения теплообменных характеристик и обеспечения экономической эффективности автономных систем теплоснабжения и горячего водоснабжения.

Ключевые слова: *полимерный солнечный коллектор, плоский солнечный коллектор, композиционный абсорбер, полимерная матрица, алюминиевый порошок, графит, Al_2O_3, наноразмерный наполнитель, теплопроводность, энергетическая эффективность, эксергетическая эффективность, LCOH.*

Introduction.

Worldwide, extensive scientific and applied research is being conducted on the integration of solar energy technologies into autonomous heat supply systems, enhancement of the energy efficiency of solar collectors, intensification of heat transfer processes occurring within these systems, and improvement of existing structural designs [1,2]. In this context, particular emphasis is placed on the development of absorber materials with enhanced thermal conductivity based on functional composites comprising polymer matrices, metallic powders, and nanodispersed additives; optimization of the compositional ratios of these materials; identification of the relationships governing the effects of composite composition on thermophysical and mechanical properties; derivation of mathematical correlations; and evaluation of effective thermal conductivity using the Maxwell model. Furthermore, the development of an optimal structural configuration for a polymer solar collector, formulation of mathematical models based on heat balance equations, analysis of heat transfer processes and heat transfer fluid flow dynamics through computational fluid dynamics (CFD) simulations, investigation of viscous and mixed convection (viscous–gravitational) flow regimes, determination of the calculated thermal efficiency and useful heat output, and verification of numerical results through experimental testing are considered among the key priorities and pressing challenges in this field. In addressing these challenges, improving the exergetic efficiency of solar water-heating collectors developed using polymer matrices, metallic powders, and functional composite materials represents a significant scientific and technical objective [3-4]. In particular, this involves determining the optimal design parameters of polymer-based absorber structures, optimizing the proportions of metallic and nanodispersed fillers to enhance thermal conductivity, performing computational modeling of heat transfer processes, and developing effective methods for minimizing thermal losses. These research directions are of considerable importance for improving the overall energy and exergy performance of polymer-based solar water-heating collectors [5-7].

Method and materials

Aim of the Research: The aim of this research is to conduct a comparative analysis of the design of an energy-efficient polymer solar water-heating collector, fabricated from a polymer-matrix composite material reinforced with metallic and nanodispersed fillers and intended for autonomous space heating and domestic hot water supply systems, with conventional flat-plate solar collectors.

According to the conducted scientific investigations and preliminary calculations, the development of a polymer solar collector based on functional composite materials has the potential to increase the outlet water temperature by 10-15%, useful thermal energy output by 30-35%, and exergetic efficiency by 15-20% compared with conventional flat-plate solar collectors. Preliminary economic calculations indicate that the proposed polymer solar collector, with an effective absorber area of 0.7 m^2, is expected to require a total capital investment of USD 400-500 and annual operating costs of USD 50-80. Taking into account the expected service life and discount rate, the levelized cost of thermal energy (LCOE) is estimated to range from USD 0.02 to 0.022 per MJ. These preliminary findings suggest that the proposed polymer solar collector has the potential to achieve favorable economic performance and become a competitive thermal energy source for practical applications in autonomous heating and domestic hot water supply systems.

Results

The following table presents a comparative analysis of a conventional flat-plate solar collector with a metallic absorber and a flat-plate solar collector incorporating a composite absorber fabricated from a polymer matrix reinforced with aluminum powder, graphite, and Al_2O_3 nanodispersed fillers.

Table 1.

Advantages and Disadvantages of Conventional and Polymer-Composite Absorber-Based Flat-Plate Solar Collectors

Type of Solar Collector	Advantages	Disadvantages
Conventional Flat-Plate Solar	- high thermal conductivity;	-metallic components may be susceptible to corrosion;

Collector with a Metallic Absorber	-simple design and well-established manufacturing technology; -effective application in domestic hot water supply systems; -long operational service life.	-relatively high structural weight; -thermal losses depend on ambient environmental conditions; -relatively high cost of non-ferrous metallic materials.
Flat-Plate Solar Collector with a Polymer-Composite Absorber (Polymer Matrix + Al Powder + Graphite + Al_2O_3)	-potential reduction in overall structural weight; -enhanced thermal conductivity of the polymer matrix through the incorporation of metallic and nanodispersed fillers; -potentially high corrosion resistance; -possibility of manufacturing absorber channels with complex geometries; -potential reduction in manufacturing costs through mass production; -long operational service life.	-thermal conductivity may remain lower than that of conventional metallic absorbers; -mechanical strength and dimensional stability must be ensured at elevated operating temperatures; -optimization of filler concentrations is required; -resistance to material aging, ultraviolet radiation, and thermal cycling must be experimentally evaluated.

Conclusions

The development of flat-plate solar collectors incorporating polymer-composite absorbers modified with metallic and nanodispersed fillers represents a promising approach to reducing structural weight, enhancing corrosion resistance, and improving heat transfer characteristics. However, their potential advantages in terms of energy and exergy efficiency compared with conventional flat-plate solar collectors equipped with

metallic absorbers must be systematically evaluated and validated through mathematical modeling and experimental investigations.

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