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Contents

Identifying Technological Trends and Promoting Strategies to Boost Innovation and Technology Transfer: A Case Study on the Patent Portfolio of Brazilian Public Research Institutions

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ABSTRACT

The development of innovative technologies represents a fundamental pillar for economic and social progress in countries, and understanding the opportunities for utilizing these technological solutions is a critical success factor. The dynamics of the technology transfer (TT) process are determined by the peculiarities of factors related to both the consumer market and the business environment in which scientific and technological institutions (STIs) operate. In the aerospace and defense sector, technologies have high dual-use potential and interest various industrial sectors. This manuscript explores emerging trends and the potential for TT of the intellectual property (IP) portfolio of these STIs across a diversified spectrum of significant technological areas in the industrial sectors. It is a case study applied to public STIs, seeking to understand the trajectories of technological development and anticipate their impact on the Brazilian productive sector. This focus is relevant as it addresses critical aspects affecting research, development, and innovation (RD&I) in public STIs, which are all essential to deciphering the complexities of the contemporary technological innovation ecosystem. This study offers valuable insights for researchers and managers of RD&I and TT, highlighting the critical role of technology in understanding the dynamics of innovation and managing of RD&I in the sector in focus.

Keywords: Intellectual property; Economic appropriability; Analysis of technological trends; Public institutions of science and technology; Brazilian aerospace and defense sector.

INTRODUCTION

The development of new and innovative technologies represents a fundamental pillar for the economic and social progress of countries (Fujino and Stal 2007; Levin et al. 1987; Lima et al. 2019). Supporting this development are the economic appropriations of technologies, which ensure that inventors and institutions have exclusive rights over their inventions (Encaoua et al. 2006).

By protecting inventions, the aim is to create an environment conducive to technological development, where ideas can be developed and economically exploited without the risk of being improperly appropriated by others (Barbosa 2010). This stimulates investment in new research towards innovative solutions and creates a virtuous cycle of innovation and economic growth.

These rights are not just a recognition of the effort and investment in research and development (R&D), but also a crucial mechanism for business strategies in the pursuit of competitive advantages, for improving the quality of life of people and for driving economic growth (OECD 2004).

In the complex process of research, development, and innovation (RD&I), understanding the possible opportunities, both for future R&D activities in research centers and for the industrial sector interested in incorporating and modernizing their industrial processes, developing and exploiting new products within their corporate strategies is a critical success factor.

In public scientific and technological institutions (STIs), the integration between technological development, protection of intellectual property (IP), and its transfer to the industrial sectors is, therefore, a strategic vector for the sustainable economic and technological development of countries, given their political objectives of creation and institutional operation.

In this context, governments, research institutions, and the productive sector must work together to create RD&I policies and organizational structures that promote innovation, protect inventions, and facilitate the technology transfer (TT) process (Etzkowitz 2002).

This collaborative effort not only accelerates economic development, but also ensures that the benefits of innovation are shared across society, contributing to a more prosperous and sustainable future (Edquist 1997; Lundvall, 1992). Indeed, this guarantee is a principle of the Innovation Law No. 10.973/2004 (Brasil 2004).

It is known that the dynamics of the TT process are determined by the peculiarities of a set of factors related both to the market itself and to the business environment in which research centers operate (Bozeman 2000). In this scenario, the technological issue is just one side of the prism where economic appropriations are embedded.

In the aerospace and defense sector, technologies are typically cutting-edge, featuring complex customized products and systems.

These technologies are engineering-intensive, high-performance, high-cost, and high-value-added, and are considered strategic by the producing nations and companies (Becz et al. 2010; Carvalho 2011; Schmidt 2011). These technologies have a high potential for dual use and are of interest to various industrial sectors.

The STIs that are the focus of this study are all located in São José dos Campos, state of São Paulo, a recognized Brazilian hub for aerospace and defense development: the Institute of Aeronautics and Space (IAE), the Institute for Advanced Studies (IEAv), and the Aeronautical Technology Institute (ITA). These public STIs perform teaching, research, and development activities to technologically support the needs of the agents in the innovation ecosystem and have robust competencies, derived from the high technical level of their professionals and diversified laboratory infrastructure, distributed in areas of knowledge essential for the aerospace and defense field. They execute a varied portfolio of RD&I projects in advanced technologies of manifest strategic importance for the country.

This manuscript reflects on the RD&I process in public technology-based STIs, considering the IP obtained by them, and explores emerging trends, knowledge gaps, the potential of TT from these IPs, and the dynamics of the innovation process in a diversified spectrum of industrial sectors. It focuses particularly focus on the areas of measurement instrumentation, testing, and navigation, among other significant technological sectors in which the STIs operate.

In doing so, the aim is not only to understand the trajectories of technological development, but also to anticipate the impacts of these trends on the economy (Campbell 1983; Kaminishi et al. 2014), on STIs, and on Brazilian society as a whole. This focus is relevant as it addresses critical aspects that affect RD&I, including IP management, TT management, economics, and project management, all essential for deciphering the complexities of the contemporary technological ecosystem. This holistic approach is reflected in the diversity of the industrial sectors analyzed, ranging from precision equipment manufacturing to software development and consultancy services.

Finally, this manuscript aims to contribute to the academic debate on the future of technological innovation in Brazilian public STIs, proposing future directions for research and practice. By mapping current and emerging trends, this study not only provides valuable insights for academics, developers, and policymakers in RD&I and TT, but also highlights the critical role of technology in shaping a sustainable and inclusive future. This represents a significant contribution to the understanding of innovation dynamics.

By offering a comprehensive and multidisciplinary analysis, it establishes an important milestone in the study of technologies developed in public STIs in the Brazilian aerospace and defense sector, outlining a promising path for future investigations in this vibrant and rapidly evolving field.

METHODS

The methodology adopted in this research was meticulously planned to address the complexity and diversity of data related to the innovation and technology development process, ensuring a comprehensive and in-depth analysis of trends and knowledge gaps in the fields studied. A case study methodology was applied in public STIs in the Brazilian aerospace and defense sector.

This work begins with the careful selection of sources, involving an extensive search in patent databases, both from Instituto Nacional de Propriedade Industrial (INPI) and similar bodies abroad.

Data collection presented a significant challenge, given the dispersed and often restricted nature of the necessary information.

This multifaceted approach ensured the capture of a broad range of data relevant for analysis.

A patent research and intelligence application, PatSeer, from Gridlogics, was used to support the presented analysis. As disclosed by the company, for the industrial areas related to the technologies, the Statistical Classification of Economic Activities in the European Community (NACE) was used. Regarding the categorization of patents into technological domains and subdomains, the International Patent Classification (IPC) was used.

The identification, filtering, storage, and analysis of the data were conducted by the authors aiming to extract valuable insights about emerging trends and potential knowledge gaps.

To substantiate the analysis of the collected data, a systematic review of the established literature was carried out. Systematic review methods were employed to generate trends and descriptive models. This robust theoretical basis allowed for a deep interpretation of the data, contributing to the construction of a detailed situational awareness of the field studied.

The analysis focused on identifying significant trends, rather than presenting purely quantitative results, providing a richer understanding of the emerging patterns in the sector. Data triangulation played a crucial role in validating the findings of this research.

Comparing results obtained in the case study strengthened the reliability of the insights generated, ensuring a holistic understanding of the investigated themes.

The research adopted a mixed-methodological approach (Creswell and Creswell 2021), utilizing extensive content analysis of documents and bibliographies, combined with qualitative techniques to demonstrate trends. This mixed approach allowed for a detailed exploration of the variables under study and the identification of significant associations between them.

Considered applied research, this approach aimed to generate practical knowledge to solve specific problems in the field of innovation and TT, using real and consolidated data. The applied nature of the research underscores its objective to contribute directly to innovation and technological development (Creswell and Creswell 2021; Gil 2010; Matias-Pereira 2019; Prodanov and Freitas 2013).

Finally, this research was structured to initially frame itself as an exploratory investigation, aiming to understand complex phenomena from a wide variety of sources. As the research progressed, it adopted a more descriptive character, establishing clear associations between the studied variables and outlining the current landscape of innovation and technologies in the focused STIs.

This multifaceted methodology ensured a comprehensive and detailed analysis, contributing significantly to the field of study.

RESULTS AND DISCUSSION

To present the results of this research, it is important to highlight the context and direction that guided our study. As mentioned above, an IP research and intelligence application was used to collect data from patent databases, both at the INPI and at similar institutions abroad.

From this data collection, information was filtered on the industrial sectors associated with the IPs in the Scientific Technological Institutions IAE, IEAv, and ITA portfolios. This was done by taking into account the IPs obtained, those in active use, and those that have lost their exclusive exploitation rights due to their legal expiration date. The resulting information is presented in Figs. 1-6.

Measuring, testing, and navigation instruments; watches and clocks
Basic chemicals, fertilisers, nitrogen compounds, plastics and synthetic rubber in primary forms
Cement, lime and plaster
Metal forming machinery and machine tools
Other special purpose machinery
Communication equipment
Electronic components and boards
Optical instruments and photographic equipment
Forging, pressing, stamping and roll-forming of metal; powder metallurgy
Other transport equipment
Basic metals
General purpose machinery
Motor vehicles
Man-made fibers
Manufacturing N.E.C.
Medical and dental instruments and supplies
Computers and peripheral equipment
Other chemical products
Other general purpose machinery
Computer programming, consultancy and related activities
Construction of other civil engineering projects
Construction of utility projects
Irradiation, electromedical and electrotherapeutic equipment
Other manufacturing
Rubber and plastic products
Containers for storage or transport
Pesticides and others agrochemical products
Textiles

Source: Elaborated by the authors.

Figure 1. Industry – IAE and IEAv – All IP obtained.

Measuring, testing, and navigation instruments; watches and clocks
Basic chemicals, fertilisers, nitrogen compounds, plastics and synthetic rubber in primary forms
Cement, lime and plaster
Metal forming machinery and machine tools
Other special purpose machinery
Communication equipment
Electronic components and boards
Optical instruments and photographic equipment
Forging, pressing, stamping and roll-forming of metal; powder metallurgy
Other transport equipment
Basic metals
General purpose machinery
Motor vehicles
Man-made fibers
Manufacturing N.E.C.
Medical and dental instruments and supplies
Other general purpose machinery
Computers and peripheral equipment
Other chemical products
Computer programming, consultancy and related activities
Construction of other civil engineering projects
Construction of utility projects
Irradiation, electromedical and electrotherapeutic equipment
Pesticides and others agrochemical products
Textiles

Source: Elaborated by the authors.

Figure 2. Industry – IAE and IEAv – Active IPs.

This initial direction aimed not only to map the current state of the patent portfolio of these public STIs, but also to identify knowledge gaps and opportunities for future investigations. With this in mind, the following results offer significant insights into the nature and direction of innovation, reflecting the complexity and interconnectedness of this constantly evolving field.

It should be noted that these STIs are subordinate to the Department of Aerospace Science and Technology (DCTA), an agency of the Aeronautical Command. The IAE is tasked with developing projects and activities in aeronautics, space access, and defense.

The IEAv is responsible for conducting applied research and experimental development with the future applications in aerospace technologies and systems. ITA is a university institution specializing in engineering education and research related to aerospace activities. Thus, ITA's IP portfolio contains technologies in various fields of knowledge, many originating from the teaching and research activities demanded by the companies that seek it for human resource (HR) training in stricto sensu courses.

Basic chemicals, fertilisers, nitrogen compounds, plastics and synthetic rubber in primary forms
Measuring, testing and navigation instruments; watches and clocks
Communication equipment
Cement, lime and plaster
Other special purpose machinery
Basic metals
Metal forming machinery and machine tools
Motor vehicles
Electronic components and boards
Forging, pressing, stamping and roll-forming of metal; powder metallurgy
Other manufacturing
Rubber and plastic products
Computers and peripheral equipment
Containers for storage or transport
General purpose machinery
Manufacturing N.E.C.
Medical and dental instruments and supplies
Optical instruments and photographic equipment
Other chemical products
Pesticides and other agrochemical products

Source: Elaborated by the authors.

Figure 3. Industry IAE and IEAv – DEAD (exclusive exploitation rights lost).

Based on the data presented in the Tables, some information can be inferred, which is important for mapping the technological roadmap and for strategic definition for technological innovation. The data collected, filtered, and analyzed allow a clear analysis of the status of various industries, categorized in different states of activity, namely: "ALL" (all cases), "ACTIVE" (active or ongoing cases), and "DEAD" (inactive or closed cases) for two distinct categories, "IAE and IEAv" and "ITA".

Regarding the most represented industries initially, it can be seen that in the categories IAE and IEAv and ITA, the industry of "Measuring, testing and navigation instruments; watches and clocks" appears as the most represented in terms of total and active cases. This suggests a strong concentration of activity or inventiveness in this specific segment, signaling an area of significant technological competence and potential development in the STIs. This trend not only highlights the existing capabilities in fields of high precision and advanced technology, but also points to strategic opportunities for growth and differentiation in the global scenario. Continuous and focused investments in R&D in this sector could lead to significant advances in measuring and navigation technologies, essential for various applications, from aviation and defense to space and maritime exploration, opening new horizons for the Brazilian industry

Measuring, testing, and navigation instruments; watches and clocks
Metal forming machinery and machine tools
Other transport equipment
Basic chemicals, fertilisers, nitrogen compounds, plastics and synthetic rubber in primary forms
Other special purpose machinery
Man-made fibres
Medical and dental instruments and supplies
Optical instruments and photographic equipment
Communication equipment
Manufacturing N.E.C.
Other general purpose machinery
Cement, lime and plaster
Computer programming, consultancy and related activities
Computers and peripheral equipment
Construction of other civil engineering projects
Construction of utility projects
General purpose machinery
Irradiation, electromedical and electrotherapeutic equipment
Motor vehicles
Containers for storage or transport
Other manufaturing
Pesticides and other agrochemical products
Textiles

Source: Elaborated by the authors.

Table 4. Industry – ITA – All IPs obtained.

Moreover, the development of innovative technologies in this sector can serve as a catalyst for digital transformation in other areas, including precision agriculture, smart city management, and logistics. The integration of advanced measuring and navigation instruments with emerging technologies such as the internet of things (IoT), big data, and artificial intelligence (AI) can offer disruptive solutions that enhance efficiency, safety, and sustainability. By positioning themselves at the forefront of these technologies, the studied STIs can strengthen their competitive positions, attracting international investments and partnerships.

Furthermore, the ability to innovate and produce technologically in this segment also has significant implications for national industrial and defense policy. Technological sovereignty in precision instrumentation and navigation systems is vital for national security and strategic autonomy. By developing and controlling key technologies, the STIs can ensure greater independence in critical supply chains and strengthen their position in international negotiations and alliances. This also opens pathways for the country to lead in global technical standards and norms in new technological areas.

Measuring, testing, and navigation instruments; watches and clocks
Metal forming machinery and machine tools
Other transport equipment
Basic chemicals, fertilisers, nitrogen compounds, plastics and synthetic rubber in primary forms
Other special purpose machinery
Man-made fibres
Medical and dental instruments and supplies
Optical instruments and photographic equipment
Communication equipment
Manufacturing N.E.C.
Other general purpose machinery
Cement, lime and plaster
Computer programming, consultancy and related activities
Computers and peripheral equipment
Construction of other civil engineering projects
Construction of utility projects
General purpose machinery
Irradiation, electromedical and electrotherapeutic equipment
Motor vehicles
Textiles

Source: Elaborated by the authors.

Table 5. Industry – ITA – Active IPs.

Metal forming machinery and machine tools
Containers for storage or transport
Measuring, testing and navigation instruments, watches and clocks
Medical and dental instruments and supplies
Other manufacturing
Other special purpose machinery
Pesticides and other agrochemical products

Source: Elaborated by the authors.

Table 6. Industry ITA – DEAD (exclusive exploitation rights lost).

To capitalize on this presented trend, it is essential to create and enhance a robust innovative ecosystem involving not only ITA as an academic institution and the STIs IAE and IEAv, but also other universities, research centers, startups, and industries. This includes fostering interdisciplinary collaboration, offering and seeking incentives for R&D, and supporting, more than ever, the TT and commercialization of innovations. Public policies that promote education in science, technology, engineering, and mathematics (STEM), along with the encouragement of talent formation in emerging areas, will be crucial to sustaining growth and innovation.

In the long term, it is understood that strengthening the industry of "Measuring, testing and navigation instruments; watches and clocks" can be a strategic differentiator for the Brazilian nation, not only in terms of competitive advantage and economic development, but also as a pillar for security, diplomacy, and global technological leadership. The commitment to innovation in this sector reflects a future vision where the studied STIs not only keep up with global technological trends, but also actively contribute to shaping them, benefiting Brazilian society and the international community.

On the other hand, it can also be inferred from Tables 1 and 2 that there are industrial areas with a high rate of active cases (current), which show a high rate of active cases compared to the total, indicating a good sustainability index or a lower dropout rate. For example, in the category IAE and IEAv, "Measuring, testing and navigation instruments; watches and clocks" and "Cement, lime and plaster" show a significant number of active cases relative to the total, suggesting robustness and sustainability in these areas. This phenomenon suggests not only the vitality and continuity of innovative technologies but also a lower dropout rate by developers and researchers, which can be interpreted as a sign of potential commercial and strategic success if well managed and marketed. For the Brazilian economy, it is understood that these industrial areas represent critical areas of investment and development, capable of generating lasting competitive advantages and significantly contributing to sustainable growth.

If we consider the sector of "Measuring, testing and navigation instruments; watches and clocks", the high rate of active cases reflects the continuous demand for technological innovations and an enduring capacity to maintain relevance in the global market. This suggests that the STIs can establish themselves as centers of excellence in this niche, promoting advances in precision technology and navigation systems. The development of this industry is strategic, not only for the technology sector, but also for sectors dependent on advanced instrumentation, such as defense, aerospace, and agribusiness, enhancing the economic and technological impact in the country.

On the other hand, the industrial area of "Cement, lime and plaster" demonstrates remarkable resilience, with a high proportion of active cases. This points to a solid base of innovation in construction materials, crucial for the development of sustainable and energy-efficient infrastructure.

Investing in innovation in this industrial area can lead to significant advancements in civil construction, with the development of more sustainable, durable, and climate-adaptive materials. Such innovation can position the STIs as leaders in green construction technologies and sustainable infrastructure, aligned with global demands for carbon footprint reduction.

To capitalize on these opportunities, it is crucial that the STIs invest in mission-oriented innovation policies that promote research and development in these areas, including tax incentives, funding for R&D projects, and public-private partnerships.

Collaboration among universities, research institutes, startups, and established companies will be crucial to accelerating innovation and the commercialization of emerging technologies. Moreover, strengthening programs of education and specialized technical training can ensure the availability of the necessary talent to drive these industries.

In the long term, the sustainable development of these industries has the potential to significantly transform the Brazilian economy, positioning the country as a leader in precision technologies and sustainable construction materials. This transformation would not only boost economic growth, but also contribute to addressing global challenges, such as climate change and sustainability.

Therefore, continuous and strategic investment in these areas represents a promising path for national development, offering economic, social, and environmental benefits of far-reaching significance for public STIs.

Continuing a critical and strategic analysis of Tables 1 and 2, it is understood that there is a clear difference between the STIs of applied research (IAE and IEAv) and the educational and research STI (ITA), in the distribution of cases among the industrial areas. For example, in the area of "Metal forming machinery and machine tools" there is a greater emphasis in the ITA category than in IAE and IEAv, both in terms of total and active cases, highlighting distinct trends and innovation focuses within the Brazilian context of research and development. While IAE and IEAv may cover a broader range of innovative technologies, the prominence of the metal forming machinery and machine tools industry in the ITA category suggests an intensive focus on the evolution of advanced manufacturing technologies. This contrast points to a diversified innovative ecosystem, in which different industrial segments receive varied emphases, reflecting targeted technological development strategies.

The prominence of the industrial area of "Metal forming machinery and machine tools" in the ITA category indicates a significant concentration of efforts and resources on advancing manufacturing capabilities, essential for industrial competitiveness in a globalized economy. This suggests that ITA is positioning itself to strengthen its infrastructure and capabilities in the advanced manufacturing sector, a critical field for industrial innovation, productivity, and economic growth. Such a focus could facilitate the development of disruptive technologies, capable of transforming production processes, increasing efficiency, and reducing costs, thereby providing Brazilian industries with a competitive advantage on the international stage.

Moreover, this emphasis reflects the importance of innovation at the base of the production chain, which can have multiplier effects on other sectors, such as automotive, aerospace, and construction. This implies that investments and innovations in this area can not only improve the competitiveness of directly related industries, but also boost efficiency and innovation in sectors dependent on these fundamental technologies. Thus, this trend could be a crucial vector for economic development, promoting industrial diversification and specialization in high-tech niches.

To capitalize on this trend, it is essential that ITA continues to invest R&D, technical education, and the formation of strategic partnerships between the public sector, academic institutions, and the private sector. Stimulating cross-sector collaboration and investment in emerging technologies can accelerate the innovation process, with the technological transfer and commercialization of new solutions. Moreover, policies that encourage the adoption of advanced manufacturing practices and integration into global value chains can reinforce ITA's position as a hub of innovation and manufacturing.

On the other hand, when we examine the industrial sectors with a high rate of inactive cases (DEAD), we notice that some sectors show a high number of inactive cases, such as “Basic chemicals, fertilisers, nitrogen compounds, plastics and synthetic rubber in primary forms” as seen in the IAE and IEAv category. This could indicate specific sector challenges, such as high competition, regulatory changes, or innovations that make technologies or products obsolete, revealing important nuances about the challenges faced by this sector in the Brazilian context.

This situation may be emblematic of various market and innovation dynamics, including market saturation, increasing regulatory barriers, or the accelerated pace of technological replacement, which can lead to the obsolescence of existing products and technologies.

Identifying these patterns is crucial for understanding the barriers to innovation and sustainable growth within specific sectors.

The high incidence of inactive cases in this sector suggests a need for continuous reevaluation and adaptation to market changes and regulatory demands. This could include investments in R&D to create new products and processes that are more environmentally sustainable, efficient, and in compliance with stricter regulations. Additionally, transitioning to bioplastics, organic fertilizers, and other sustainable alternatives could be a key strategy for revitalizing the sector, reducing the rate of inactivity by aligning with growing demands for greener and more responsible practices.

To address these challenges, it is crucial for companies and research institutions involved in these areas to prioritize open innovation and interdisciplinary collaboration. This may involve strategic partnerships with other universities, research centers, and tech startups, aiming to accelerate the development of new technologies and their rapid commercialization. International collaboration can also be a way to access new ideas, technologies, and markets, as well as share the risks and costs associated with innovation.

From a public or sectoral policy perspective, encouraging innovation in this sector may involve offering tax incentives, R&D grants, and support for forming innovation clusters that bring together businesses, academia, and government. Such policies can stimulate industrial modernization, sustainability, and international competitiveness. Implementing clear and stable regulatory frameworks is also crucial to providing a predictable business environment that favors long-term investments in innovation.

Finally, the high rate of inactive cases highlights an opportunity for the focused STIs to reposition themselves as leaders in sustainable innovation within this sector. By adopting strategies geared towards a circular economy, resource efficiency, and reducing the environmental footprint, the country cannot only overcome the specific challenges faced by this sector, but also set new standards for sustainability and technological innovation. This direction would not only strengthen the role of public STIs on the global scene as an innovative and responsible nation, but also contribute to sustainable economic development and longterm industrial resilience.

After analyzing the previous premises, clustering and trying to focus on clear trends for these authors, some general trends and insights can be presented in summary:
There is considerable diversity in the industrial areas listed, ranging from measuring equipment to chemicals and machinery.

- This reflects the breadth of potential for innovation and industrial activity.
- The presence of categories such as "Computer programming, consultancy and related activities" suggests the increasing importance of the technology and consultancy services sector, although the total number of cases is relatively low.
- Industrial areas with few cases, such as "Textiles" and "Pesticides and other agrochemical products", may represent specific niches or areas with higher barriers to entry or regulation.
- These trends are quite enlightening, allowing for a better analysis of the current situation and promoting R&D policies for the coming years, taking advantage of opportunities and acquired competencies.

CONCLUSIONS

In light of the data and insights presented in this study, it is crucial to reflect on the trends and gaps identified throughout the research process and on the management of the technological innovation process and R&D management. These processes aim to promote technological transfer to the Brazilian productive sector.

A detailed analysis of trends and dynamics in the areas of innovation and technological development in various industrial areas allows us to infer that these trends extend beyond mere technological progress, pointing to significant transformations in the economic and social scenario.

This summary seeks to consolidate the main findings, discuss their relevance to the field of study, and suggest directions for the strategic management of technological innovation and future research and development. This conclusion not only encapsulates the results of our study, but also highlights the vital role of technological innovation in shaping the future of industries and society as a whole.

Thus, an analysis of the general trends and insights inferred from the data obtained from the patent portfolios of the public STIs studied, as set out in the Tables presented, reveals a varied innovative potential with significant implications for the technological and economic future of the Brazilian productive sector. The diversity of industrial areas, ranging from measuring equipment to chemicals and machinery, underlines the wide range of possibilities for innovation and industrial activity that these STIs offer the sector. This variety not only reflects the opportunities for development and specialization in multiple sectors, but also highlights the technological complexity of the aerospace and defense sector's innovation ecosystem.

The prevalence of categories such as "Computer programming, consultancy and related activities" indicates the growing importance of the technology and consulting services sector. While the total number of cases is lower compared to other sectors, this suggests an emerging focus on information technology and digital services, areas recognized globally for their disruptive potential and ability to accelerate digital transformation across industries. The public STIs under study have the potential to establish themselves as leaders in R&D and technological innovation within the broader technological innovation ecosystem in Brazil and even in Latin America. This would be facilitated by their technology talent base and the growing digital infrastructure available.

Conversely, industrial sectors with few cases, such as "Textiles" and "Pesticides and other agrochemical products," may indicate specific niches or areas that face higher barriers to entry and stricter regulation. These sectors present opportunities for targeted innovation and the development of sustainable and environmentally friendly technologies that can meet global demands for cleaner and more efficient production practices. Investment in R&D in these areas can position STIs as leaders in sustainability and green technologies.

To capitalize on these opportunities, it is crucial that these STIs strengthen the innovation ecosystem in which they operate through proactive action via strategic management of the technological innovation process, including R&D management focused on the needs and interests of the agents in this ecosystem and effective management of the transfer of technological solutions to the Brazilian productive sector.

It is similarly crucial that they actively engage in the formulation of mission-oriented innovation policies that prioritize STEM, technological innovation management, R&D incentives, and collaboration between universities, research institutes, and industry.

The development of international partnerships represents another vital factor in this strategy to reinforce the ecosystem, facilitating access to global markets and collaboration on cutting-edge research projects.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Brandão Neto N; Writing – Original Draft: Brandão Neto N and Faria LA; Supervision and Analysis:

Melo FCL and Faria LA; Validation and Review: Melo FCL; Final approval: Brandão Neto N.

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All dataset were generated or analyzed in the current study.

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Performance Enhancement of a Variable Cross-Sectional Area Square Pipe Solar Heater

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ABSTRACT

Recently, solar energy has become most favorable source of energy. It is sustainable and environmentally friendly, and one of the most common application of solar energy is the solar water heater, which has a wide commercial and domestic applications. To enhance the performance of this device, many modifications are recommended. The enhancements may involve changes in pipe shape or materials or in absorber plate manufacturing, or sometimes by using a thermal storage tank to maintain heating. In this study, a variable cross-sectional area pipe is used to enhance heat transfer. Firstly, the vertical length is increased at the outlet to 1.2-1.8 ratios, while the horizontal sides remain constant. Then, for the same ratio, the horizontal sides are varied while the vertical sides remain constant. Finally, both the vertical and horizontal sides are increase. A three-dimensional numerical analysis is used to investigate the conjugated heat transfer and the flow characteristics in the pipe under study for each case. FLUENT ANSYS 17.2 is used to achieve this analysis using finite volume technique. Energy, Navier-Stokes, and continuity equations are solved at constant heat flux condition for a range of Reynolds numbers from 100 to 500. The hydraulic-thermal function ε is adopted in this study. The best increase in ε is 48%, achieved in the case of changes to both vertical and horizontal dimensions at a ratio of 1.8. The lowest percentage of decrease in pressure drop is 9.7%, and the highest temperature difference found is and 45.5% for the same case when compared with the uniform case for Reynolds number of 100. The present work is validated with another study adopting Shah's empirical relation with a very good agreement.

Keywords: Solar energy; Solar water heater; Square pipe; hydraulic-thermal function; ANSYS.

INTRODUCTION

A Solar collector collects the incident solar radiation and transfers the absorbed heat to the fluid that flows through attached pipes. To insure that the heat transfers to the fluid with minimum losses, the heat transfer phenomena must be enhanced (Patel et al. 2005).

Heat transfer enhancement is one of the essential tasks in most mechanical applications (Webb and Kim 2005). An appropriate improvement technique must be chosen, considering the cost and size of the arrangements (Massoud 2007).

Two essential phenomena occur in the case of fluid flow in a pipe if it subjected to constant heat flux. They are the conjugated heat transfer and fluid friction. The latter causes pressure drop, velocity loss, and change in fluid temperature. Changing the tube, cross-sectional area has a significant effect on these two phenomena (Lee et al. 2013).

Many researches have studied this phenomenon experimentally, numerically, or analytically by solving of energy and flow equations. Vahidifar and Kahrom (2015) concluded experimentally that an increase in the convective heat transfer coefficient in any heat exchanger pipes can reduce the total heat exchanger size, weight, and as a result the cost. In their experiments, the enhancement was achieved by an electrical heat source (coil) located inside the pipe, which increased roughness and turbulence, resulting in a 128% enhancement in heat transfer. Negi et al. (2019) proved that the microchannel overall performance depended largely on Knudsen and Reynolds numbers. A computational fluid dynamics (CFD) analysis was conducted in order to simulate a counter microchannel flow under slip and no slip conditions. It was concluded that as Reynolds and Knudsen numbers increased, the pressure drop increased, so the effectiveness reduced. Bashir et al. (2019) deduced experimentally that the heat flux applied and the flow direction had no effect on the Nusselt number in the laminar regime. They also proved that the Nusselt number did not have a value of 4.36 for fully developed laminar flow in the range of Reynolds numbers larger than 1,000. Srivastava et al. (2017) used a constant heat flux convergent – divergent microchannel heat sink to investigate the channel thermal resistance, the friction coefficient, and the maximum temperature of substrate for a range of Reynolds number from 120 to 900, with and without ribs. It was found that using their configuration with cavities and ribs could reduce up to 40% in thermal resistance and the substrate temperature constant approximately. An increase in the Nusselt number of 15 to 40% was observed for the studied range of Reynolds numbers. However, their configuration poorly enhanced heat transfer, and its effectiveness gradually decreased in the case of high Reynolds numbers due to the high-pressure drop that occurred. Laila et al. (2021) adopted heat transfer model for a convergent-divergent rectangular channel. In their model, the governing equations were solved numerically in Cartesian coordinates. It was confirmed that the numerical solution was independent of slope direction (i.e., whether the channel area diverges or converges). Therefore, the solution achieved for the upper half was also considered for the lower part. It was concluded that the temperature profile decreased in the divergent flow and it increased in the convergent zone.

Salih and Yaseen (2021) carried out a two-dimensional laminar forced convection study of Al2O3-H2O nanofluid flow in a circular pipe to analyze the fluid flow and the thermal behavior under constant heat flux conditions.

The simulation achieved numerically with the aid of COMSOL software, the continuity, momentum, and energy were discretized and solved by the finite element method for Prandtl number = 5.42 and a range of Reynolds numbers ≤ 2,000. The results indicated that the use of Al_2O_3 nanoparticle enhanced the average heat convection coefficient by 10% for a volume fraction of 5%, with a maximum pressure drop of 15%. To validate their model, the empirical Shah equation was used and the results showed good agreement.

Gheynan et al. (2019) studied the effects of nanoparticle concentration and diameter on the temperature fields of turbulent non-newtonian carboxymethylcellulose (CMC)/copper oxide (CuO) nanofluid in a three-dimensional microtube. Low- and high-Reynolds turbulent models were used in the modeling process. Interesting results were obtained, which can be helpful for engineers and researchers working on the cooling of electronic devices. A numerical investigation of water/Al_2O_3 nanofluid in a T-shaped enclosure with lid-driven by applying magnetic field was conducted by Toghraie (2017). For different values of Richardson, Hartmann numbers and void fraction. It was revealed that applying a magnetic field significantly effects the temperature domain (heat transfer) and fluid flow, considerably reducing the fluid's circulation mechanisms. Barnoon et al.

(2019) investigated non-newtonian heat transfer and flow of nanofluid in a permeable enclosure with two cylinders embedded in the cavity with and without the thermal radiation effect. The study was conducted for different values of Rayleigh and Darcy numbers with different void fractions and cavity angle values. It was indicated that the changes in the cavity angle had a significant effect on heat transfer values.

In the present study, a three-dimensional analysis is conducted to simulate a water laminar flow in a variable cross-sectional area square pipe. The objective is to investigate the flow characteristics and heat transfer performance under a constant heat flux of 3,000 $w \cdot m2$

on the (top) wall. For values of Reynolds numbers ranging from 100 to 500 and different divergent ratios in vertical sides alone, horizontal sides alone, and in both two sides, the temperature difference and pressure drop through the pipe are calculated to display the effects of these two parameters on the thermal-hydraulic performance function ε.

The governing equations

A numerical investigation is conducted for a water flow in a square pipe of 1 m length, with an internal side length of 0.05 m and a thickness of 0.05 m, referred to as the square pipe case shown Fig. 1. Then the value of the vertical side increases at the outlet by a ratio of 1.2-1.8 for a constant value vertical side at the inlet. The horizontal sides then increase at the outlet in the second case for the same ratio range, and finally all sides are enlarged. The governing equations in each case are the continuity (Eq. 1), momentum (Eq. 2) and energy (Eq. 3) under the following assumptions:

- Forced convection, three-dimensional laminar steady state flow;
- Incompressible newtonian fluid;
- Body forces and viscous dissipation are ignored.

Continuity equation:

$$\nabla . \rho \vec{V} = 0 \tag{1}$$

Momentum equation:

$$\nabla . \left(\rho \vec{V} \vec{V}\right) = \nabla P + \nabla . (\mu \nabla^2 \vec{V}) \tag{2}$$

Energy equation:

$$\nabla . \left(\rho \vec{V} C_p T\right) = \nabla . (K \nabla T) \tag{3}$$

For the above three equations, the boundary conditions applied are no slip and uniform flow velocity at the inlet. Zero pressure at the outlet. The thermal conditions are constant inlet temperature and constant heat flux of 3,000 w·m^2 at the duct upper surface.

The Nusselt number is given by Eq. 4:

$$Nu_x = \frac{h_x D_h}{k_f} \tag{4}$$

where h_x is local heat transfer coefficient, which can be given shown by Eq 5:

$$h_x = \frac{q_x}{(T_w - T_b)} \tag{5}$$

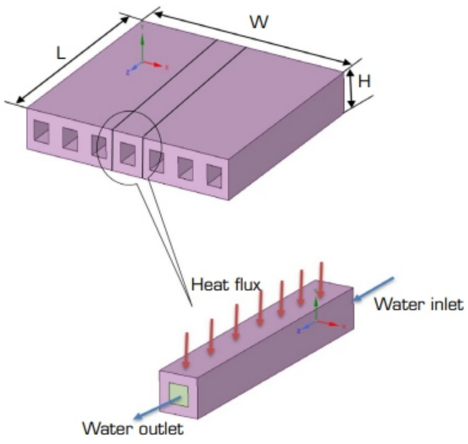
Average coefficient of heat transfer is represented by Eq. 6:

$$h_{av} = \frac{1}{L} \int_0^L h_x dx \tag{6}$$

The hydraulic-thermal factor ε is given by Mashaei *et al.* (2012), as shown in Eq 7:

$$\varepsilon = \frac{h_{av}}{\Delta p^{1/3}} \tag{7}$$

where Δp is the pressure drop through the duct.



Source: ANSYS.

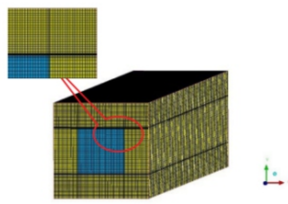
Figure 1. The square pipe geometry.

Test of grid dependency

To ensure accurate results for minimum grid size four mesh size are tested, which are 40 × 40 × 250, 40 × 40 × 350, 60 × 60 × 450, and 75 × 75 × 550 in x, y, and z directions. The used mesh is hexahedral unstructured type, as shown in Fig. 2. The selected mesh size is 60 × 60 × 450, which makes the more accurate results for the bulk temperature, as shown in Fig. 3. Also the selected mesh makes a maximum error of 0.48% if the values of Nusselt numbers from the model under study are compared with the results from the empirical Shah Eq. 8 (Kakac et al. 1987; Shah and London 1987), in the case of constant heat flux subjected to pipe of pure water inside flow at Reynolds number of 900. The result shows an excellent agreement as displayed in Fig. 4

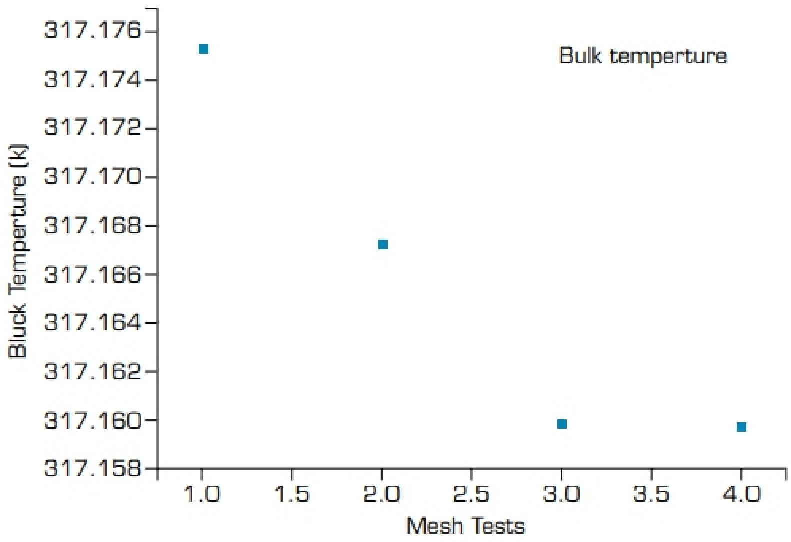
$$Nu_x = \begin{cases} 0.77\, X_*^{-1/3} & X_* \leq 0.01 \\ 3.657 + 6.874(10^3\, X_*)^{-0.488}\, e^{-57.2\, X_*} & X_* > 0.01 \end{cases} \tag{8}$$

where Nu_x given by eq. (4) and $X_* = \frac{x/D_h}{Re_{pr}}$.



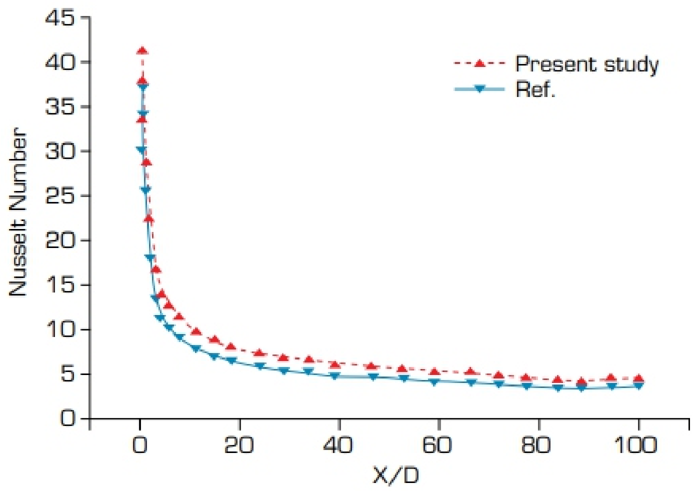
Source: ANSYS mesh.

Figure 2. The mesh generated for uniform duct case.



Source: ANSYS analysis.

Figure 3. Bulk temperature versus flow direction for different mesh sizes.



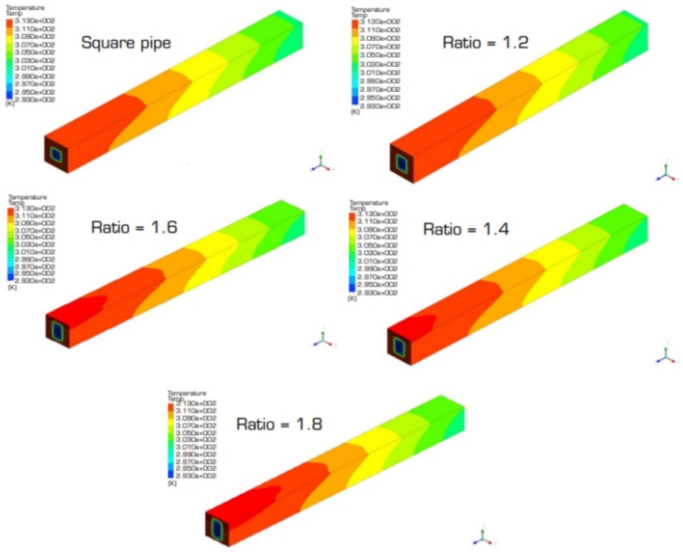
Source: ANSYS analysis.

Figure 4. A comparison between the studied model and the results from Shah equation for water flows inside a duct at Reynolds number of 900 and subjected to constant heat flux.

RESULTS AND DISCUSSION

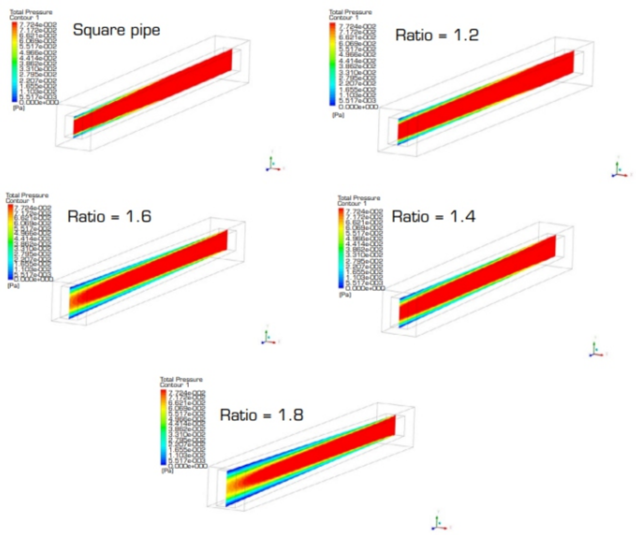
By solving the computational model mentioned, many pressure and temperature contours can be obtained and the flow characteristics can be illustrated in the following figures for each case under study.Temperature contours for different expansion ratios in the case of expanded vertical sides at the pipe exit are shown in Fig. 5. It can be observed that, as the expansion ratio increases, the temperature at the pipe exit increases, which means the heat transfer phenomena enhance. As the ratio increases, the pipe cross-sectional area increases, so the flow remains longer inside the tube and the convective heat transfer becomes more active.

The maximum increase in temperature percentage is 7%. In Fig. 6 the pressure contours the same case above are shown for different expansion ratios. The pressure decreases as the ratio increases, which is a normal behavior; as the expansion ratio increases, the pressure forces are distributed over a larger area, so the pressure values decrease. The behavior in Figs. 7 and 8 is the same as in Figs. 5 and 6 for the horizontal sides increasing at the outlet with the same expansion ratios because the change in area is same. In Figs. 9 and 10, the expansion achieved in all sides, so the area is the larger than in the previous two cases and the changes are more apparent. More significant increases in temperatures are achieved, which means there is a more enhancement in heat transfer phenomena.



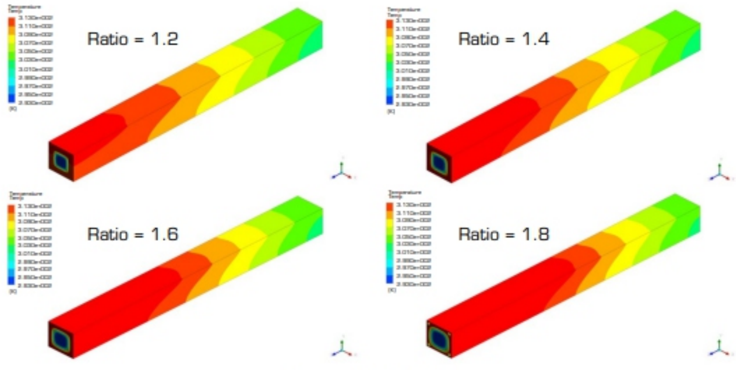
Source: ANSYS analysis.

Figure 5. Temperature contours in the case of expanded vertical sides at different expansion ratios.



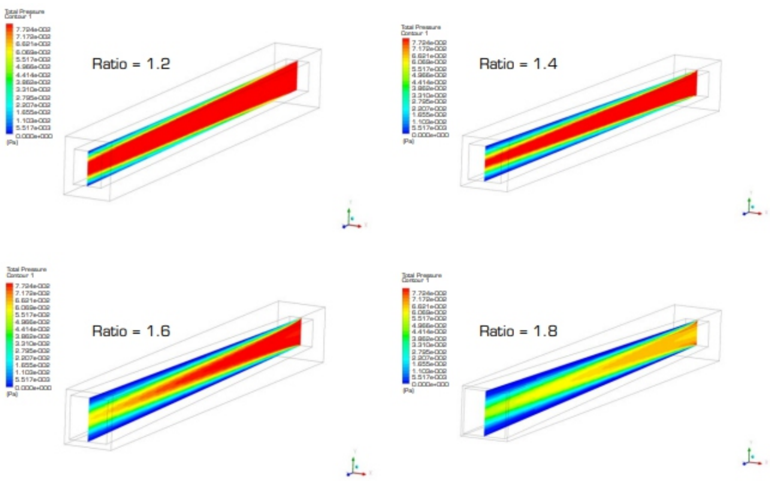
Source: ANSYS analysis.

Figure 6. Pressure contours in the case of expanded vertical sides at different expansion ratios.



Source: ANSYS analysis.

Figure 9. Temperature contours in the case of all sides expanded at different expansion ratios.



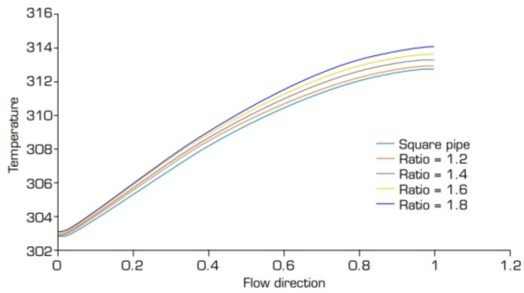
Source: ANSYS analysis.

Figure 10. Pressure contours in the case of all sides expanded at different expansion ratios.

Figures 11-13 show the temperature distributions along the flow direction for all cases under study. The temperature difference between the case of a 1.8 ratio and the square pipe reaches to 1.4 °C in the case of vertical side expansion at the pipe outlet. This value increases to 2.4 °C in the second case at the same ratio, as shown in Fig. 12. The maximum temperature difference of 9 °C (at the pipe exit between the case of a 1.8 ratio and the square pipe) occurs in the third case when all the pipe sides are expanded at the outlet. A large temperature difference was achieved due to the increase in area, as shown in Figs. 12 and 13.

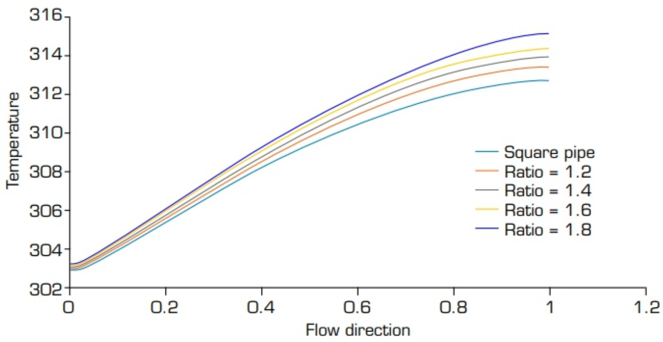
Figures 14-16 illustrate the pressure drop through the flow direction for the three cases studied. In Fig. 14, the maximum pressure drop occurs in the case of the square pipe, and as the expansion ratio increases, the pressure drop values decrease until the enhancement reaches to 72% at a ratio of 1.8. The same enhancement ratio is obtained in the second case, as shown in Fig. 15 because the same change in area occurs.

In the third case, the enhancement in pressure drop reaches to 153% at the same ratio because the area is doubled.



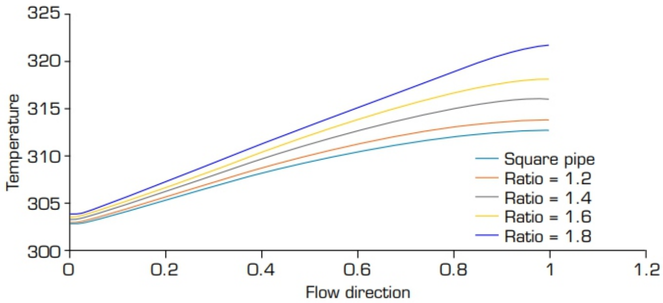
Source: ANSYS analysis.

Figure 11. Temperature distribution for different expansion ratios in the case of expanded vertical sides at the pipe exit.



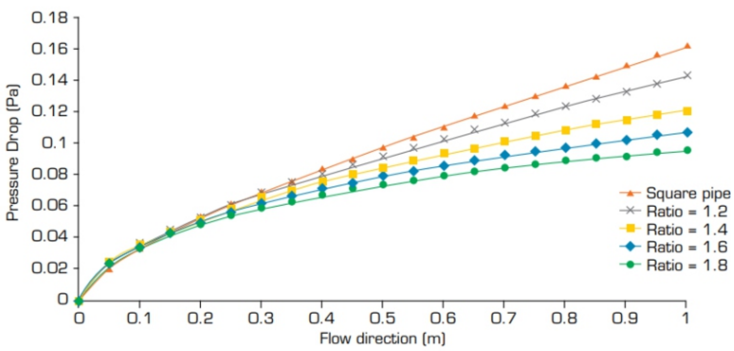
Source: ANSYS analysis.

Figure 12. Temperature distribution for different expansion ratios in the case of expanded horizontal sides.



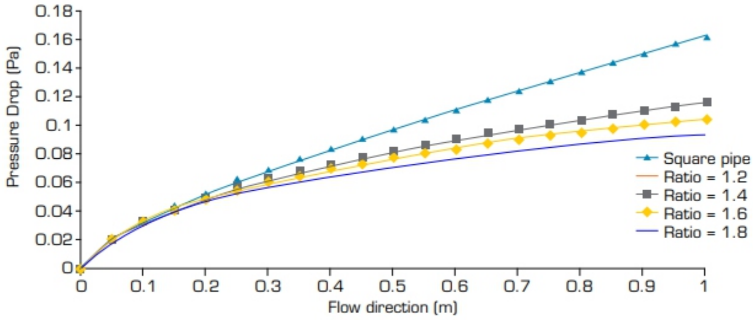
Source: ANSYS analysis.

Figure 13. Temperature distribution for different expansion ratios in the case of expanded both vertical and horizontal sides.



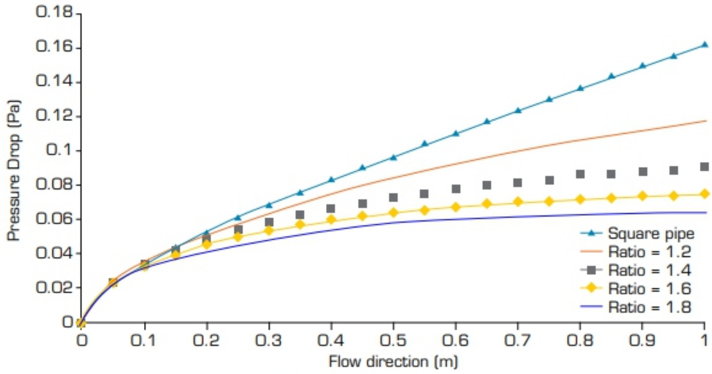
Source: ANSYS analysis.

Figure 14. Pressure drop with the flow direction in the case of expanded vertical sides for different expansion ratios.



Source: ANSYS analysis.

Figure 15. Pressure drop with the flow direction in the case of expanded horizontal sides for different expansion ratios.

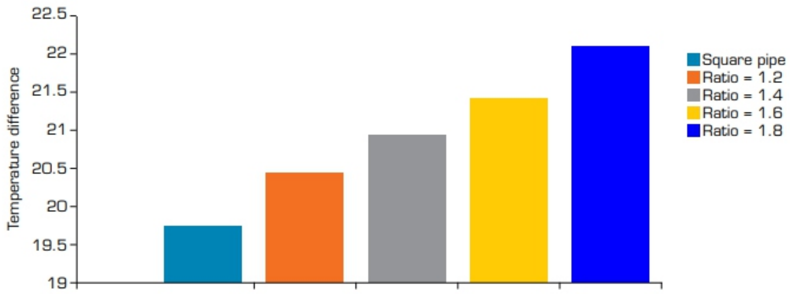


Source: ANSYS analysis.

Figure 16. Pressure drop with the flow direction in the case of all sides expanded for different expansion ratios.

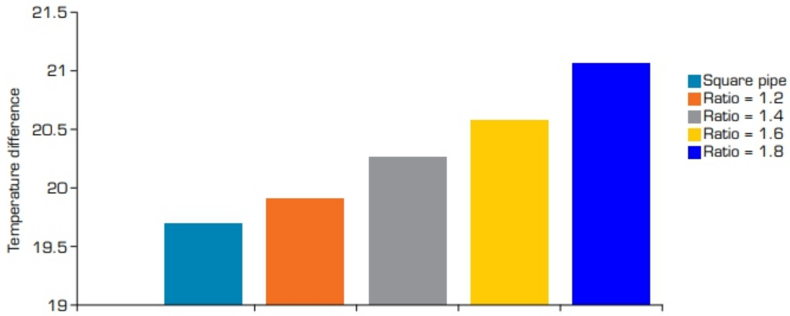
Figure 16. Pressure drop with the flow direction in the case of all sides expanded for different expansion ratios.

Figures 17-19 show the temperature difference between pipe inlets to pipe exit at all cases under study at different expansion ratios. It is so obvious that the third case records maximum temperature difference percentage reaches to 45.5%. This means the third case witnessed a maximum heat transfer rate because of the larger area if it compared with previous two cases.



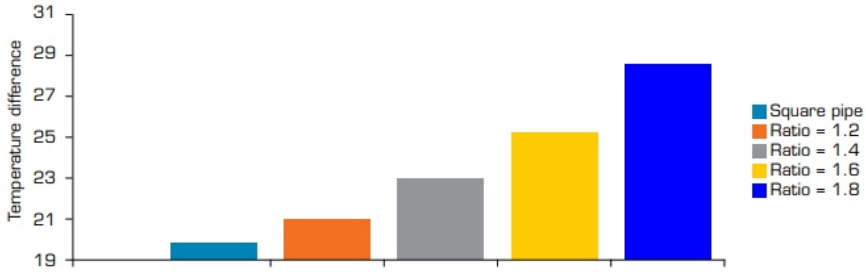
Source: ANSYS analysis.

Figure 17. Temperature difference along flow direction for different expansion ratios in the case of expanded vertical sides.



Source: ANSYS analysis.

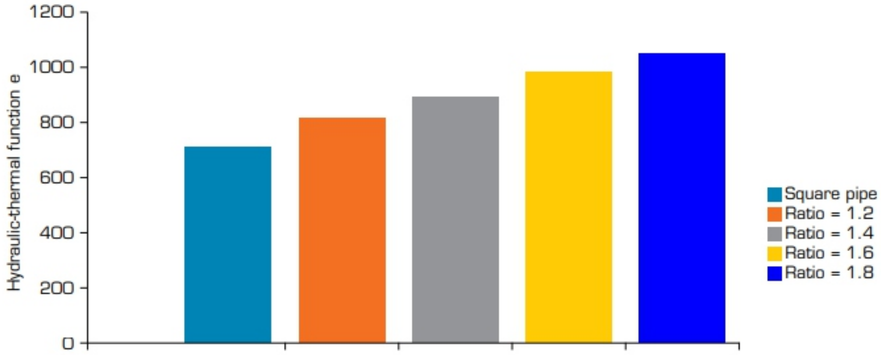
Figure 18. Temperature difference along flow direction for different expansion ratios in the case of expanded horizontal sides.



Source: ANSYS analysis.

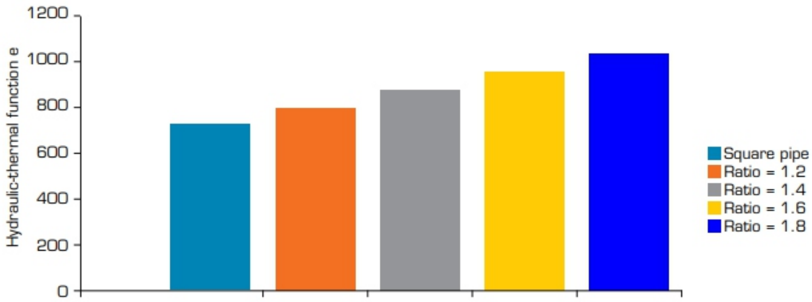
Figure 19. Temperature difference along flow direction for different expansion ratios in the case of expanded both vertical and horizontal sides.

Figures 20-22 show the values of hydraulic-thermal performance function ratio in all cases under study for all studied expansion ratios. As the expansion ratio increases, the area increases, which means the heat transfer phenomena enhances, then the hydraulic ratio increases. The maximum increase occurs at third case, when the expansion ratio reaches to 1.8.



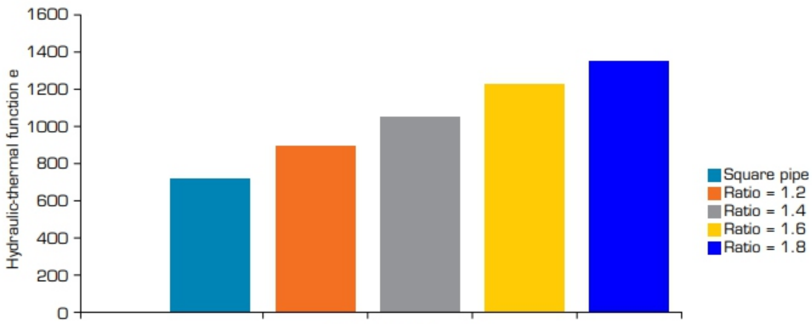
Source: ANSYS analysis.

Figure 20. Hydraulic-thermal performance function for different expansion ratios in the case of expanded vertical sides.



Source: ANSYS analysis.

Figure 21. Hydraulic-thermal performance function for different expansion ratios in the case of expanded horizontal sides.



Source: ANSYS analysis.

Figure 22. Hydraulic-thermal performance function for different expansion ratios in the case of all sides expanded.

Figure 22. Hydraulic-thermal performance function for different expansion ratios in the case of all sides expanded.In Table 1, the ratio of the hydraulic-thermal performance functions for each case to the same function in the case of square pipe is presented. In the first two cases, there are no large significant changes (the total area remains constant). In the third case, a noticeable increase is observed, with the area doubling. Consequently, the heat transfer significantly improves, reaching an enhancement of 48%.

Table 1. The ratio of hydraulic-thermal performance functions in each case at different expansion ratio to the hydraulic-thermal performance functions of square pipe.

Cases	Ratio			
	1.2	1.4	1.6	1.8
Vertical sides expansion at exit	114.327	126.135	137.081	146.689
Horizontal sides expansion at exit	110.172	123.137	134.367	144.325
Both vertical and horizontal sides expansion	125.525	147.996	172.455	186.845

Source: ANSYS analysis.

CONCLUSIONS

By analyzing the heat transfer phenomena and the pressure drop through the cases under study, it can be concluded that:

- A maximum temperature difference of 45.5% can be recorded if all sides are expanded at the outlet at a ratio of 1.8;
- The enhancement in pressure drop reaches to 153% at a ratio of 1.8 in the third case. As a result, the hydraulic-thermal performance function is increased by 48%.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Ahmed SS; Methodology: Hashim NA, Ahmed SS; Software: Ahmed SS, Hashim NA; Validation:

Hashim RH, Al-Fatlwe FMK; Formal analysis: Ahmed SS; Investigation: Hashim NA; Resources: Al-Fatlwe FMK; Data Curation: Hashim NA, Ahmed SS; Writing - Original Draft: Hashim NA; Writing - Review & Editing: Ahmed SS; Final approval: HashimNA.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable.

FUNDING

Not applicable.

ACKNOWLEDGMENTS

Not applicable.

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Assessment of Indicators for Updating Adjacency Matrix of Self-Organizing Flying Ad Hoc Network

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ABSTRACT

The concept of a swarm of drones assumes the presence of a wireless ad hoc network, in which drones are network nodes and exchanging information with each other. This article is devoted to studying the behavior of an ad hoc network in a transient mode and assessing the characteristics of updating local adjacency matrices (LAM), which allow network nodes to autonomously form packet transmission routes. Using a simulation model, a comparison was made of two multiple access methods to a common data transmission channel in the process of updating matrices: cyclic and random (slotted ALOHA). The simulation results made it possible to determine areas of their effective application: slotted ALOHA is advisable to use with relatively high probabilities of packet distortion (of the order of 0.1 and higher), a numerous nodes (more than 40), and low network connectivity, and cyclic access (CA) is effective at a low level of distortion. It is shown that the completion of the process of updating adjacency matrices (AM) can be judged by such indicators of the exchange of routing information as the achievement of a certain threshold of the number of transmissions and a decrease in the level of network traffic.

Keywords: Unmanned aerial vehicle; Swarm; Flying Ad Hoc Network; Adjacency matrix; Cyclic access; Slotted ALOHA.

INTRODUCTION

The development of telecommunication technologies and robotics has led to the practical implementation of the concept of a swarm of drones that act in concert and perform a common task. This approach opens up new opportunities and advantages in the field of unmanned systems, as it is shown in the Table 1 (Chen et al. 2020).

To perform the target function of the swarm, it is necessary to organize the rapid exchange of information between drones using an appropriate communication network. Since drones are constantly moving in space, the communication network must automatically adjust to changes in their position. In the scientific and technical literature, such networks are called wireless ad hoc networks, in which drones are network nodes and exchanging information with each other (Agrawal et al. 2022; Cheng et al. 2013).

If in wired networks and managed wireless networks data flows are controlled using routers and access points, then in ad hoc networks such control is carried out decentralized using various dynamic routing protocols.

Table 1. Comparative characteristics of a system with a single drone and a swarm.

Features	Single drone	Swarm
Survivability	Poor	High
Scalability	Limited	High
Speed of mission	Slow	Fast
Autonomy	Low	High
Cost	High	Low
Communication needs	High	Low
Radar cross-sections	Large	Small

Source: Elaborated by the authors.

There are three main types of ad hoc networks: Mobile Ad Hoc Network (MANET) (Gupta et al. 2018; Hasan et al. 2020), Vehicular Ad Hoc Network (VANET) (Rehman et al. 2013; Zeadally et al. 2010), and Flying Ad Hoc Network (FANET) (Bekmezci et al. 2013; Sahingoz 2014; Sobhy et al. 2016). Table 2 (Tareque et al. 2015) shows a comparative assessment of these networks according to various criteria, from which it follows that FANET, whose subscribers are unmanned aerial vehicle (UAV), has the most rapidly changing topology. At the same time, the node density in it is low, i.e., subscribers are located at a fairly large distance from each other.

Table 2. Comparative evaluation of FANET, VANET, and MANET.

Criteria	Ad Hoc Network types		
	FANET	VANET	MANET
Node mobility	High compactness	Medium compactness	Low compactness
Mobility model	Usually predetermined but special mobility models for independent multi-UAV systems	Steady	Arbitrary
Node density	Low thickness	Medium thickness	Low thickness
Topology change	Rapid and speedy	Average speedy	Slow and steady
Radio propagation model	High above the ground level, LoS is accessible for most of the cases	Close to ground, LoS is now accessible for all cases	Very close to ground, LoS is not accessible for all cases
Power consumption and network lifetime	Needed for mini-UAV, but now needed for small UAV	Not needed	Need of energy efficient protocols
Computational power	Very big	Average	Limited
Localization	GPS, AGPS, DGPS, IMU	GPS, AGPS, DGPS	GPS

Source: Elaborated by the authors. LoS = line of sight.

For FANET, as for other types of ad hoc networks, a pressing scientific and technical challenge is the development of routing protocols that quickly adapt to frequent and unpredictable changes in the network topology. There are quite a few approaches to the development of routing protocols in FANET, a detailed review of which is given in (Guillen-Perez et al. 2021; Khan et al.2019; Leonov 2017; Mahalakshmi and Nithya 2018; Yadav et al. 2015). In this regard, it is also necessary to note the works (Kaur et al. 2021; Li et al. 2019; Madridano et al. 2020; Malecki et al. 2021; Wu et al. 2022) that consider the issues of adapting a swarm to the failure of individual network nodes and methods of route planning using various algorithms.

Also, a numerous works are devoted to analyze the effectiveness of various routing protocols in FANET. In Kim et al. (2023), a study was carried out on the influence on the characteristics of FANET of such parameters as the density of UAV and the speed of their movement for various protocols and mobility models. In Yang and Liu (2019), a FANET network with the Dynamic Source Routing (DSR) protocol operating in conjunction with a continuous Hopfield neural network was simulated. It is shown that the use of artificial intelligence can increase network throughput and reduce the average network delay when transmitting data from UAV. Modeling the behavior of FANET with Ad Hoc On-Demand Distance Vector (AODV) and Location-Aided Routing (LAR) protocols using the NS2 simulator, carried out in (Kumar et al. 2020), made it possible to compare these protocols in terms of the probability of packet delivery, their average delay time and network throughput. In Guillen-Perez et al. (2021), a comparative analysis of the probability of packet loss and network throughput of routing protocols Babel (based on distance-vector), Better Approach to Mobile Ad-hoc Networking (BATMAN) and Optimized Link State Routing Protocol (OLSR) was conducted. A similar study was carried out in (Alkhatieb and Felemban 2020) for OLSR, AODV, DSR, Temporally Ordered Routing Algorithm (TORA), and Geographic Routing Protocol (GRP) under different mobility models: Random Waypoint Mobility, Manhattan Grid Mobility Model, Semi-Random Circular Movement and Pursue Mobility Model.

These and several other works analyze the behavior of FANET for various routing protocols, data rates, and models of subscriber behavior in the stationary mode. However, the analysis of FANET characteristics not only in the stationary mode, but also in non stationary conditions, i.e., when it's topological structure changes, is of great scientific and practical interest. This article is devoted to the analysis of the characteristics of updating local adjacency matrices (LAM), which allow network subscribers to autonomously form packet transmission routes. The need to periodically update information about the current network configuration in LAM is due to the fact that its topology changes due to the mutual movement of UAV. To transmit this routing information, it is necessary to either allocate part of the communication channel capacity (with frequency-division multiplexing [FDM]) or interrupt the transmission of information packets to exchange routing information (with time division multiplexing [TDM]). The purpose of this work is to estimate the time required to update LAM in FANET with TDM when using various algorithms for accessing the communication channel and in the presence of distortions in the transmitted data.

Theoretical basis The effectiveness of using a UAV swarm is significantly increased when the following basic conditions are met (Campion et al. 2018; Chen et al. 2020; Pirmagomedov et al. 2019): the group is autonomous, i.e., information interaction with a remote-control point is minimal or absent; data exchange within the swarm is carried out using a communication network, the nodes of which are UAV themselves that are part of the swarm.

The presence of a communication network allows each UAV to transmit information to any other UAV in two possible ways: directly via a direct communication channel (we will call such UAV adjacent); by relaying through other UAV if the transmitting and receiving UAV do not have a direct communication channel.

Possible data transmission routes (directly over the forward link or through relay nodes) are determined by the network structure, which is constantly changing due to the movement of UAV relative to each other. Thus, each node must have up-to-date information about the network structure and the ability to route both its own and transit packets. The basis for constructing a route is the LAM (Liu et al. 2008; Singh and Sharma 2012), which contains information about the characteristics of communication channels between adjacent nodes (i.e., those that currently have a direct communication channel). The mutual movement of UAV changes the network topology, so there is a need for each node to periodically update information about the current network configuration.

To solve the problem of updating LAM, it is necessary to organize the exchange of this information between network nodes.

Since the speed of information transmission over a communication channel is finite, it is necessary to allocate a certain amount of time for TDM or part of the bandwidth for FDM to update the matrices. The lack of clear LAM update frequency criteria can result in: to an unjustified increase in the time allotted for updating matrices, which accordingly reduces the time for transmitting packets; to the premature start of transmission of information packets, which accordingly does not allow LAM to be completely updated.

In both cases, these factors lead to a decrease in the efficiency of FANET operation. Therefore, an urgent scientific and practical task is to estimate the time required to update LAM network with dynamic routing when using various access algorithms.

Below we will consider such a network of N nodes, communication between which is carried out via a radio link with TDM. We will also assume that the communication channel between nodes is half-duplex. The model of such a network can be represented as a graph, the vertices of which are the network nodes, and the edges of the graph model the communication channel between the corresponding nodes (Diestel 2005; Wilson 1996). Since the channels are half-duplex, the edges of the graph are bidirectional.

In the general case, the graph can have markings that reflect the technical parameters of the communication channel: its load, cost, transmission time, etc. In this article, we will only take into account the fact of the presence of a channel between two nodes – there is a direct channel between the corresponding nodes or there is none.

The network graph can be represented as an NxN size LAM. The element M(k,n) of this matrix is equal to one if nodes numbered k and n are connected by a channel, and equal to 0 otherwise (Aldous and Wilson 2003). Since the arcs are non-directional, the matrix will be symmetrical. From adjacency matrices (AM), all nodes associated with a selected node can be determined.

The procedure for determining connected nodes is iterative, the procedure of which is described below. We denote by: A(k) the set of nodes that are directly connected to node Yk, by KAC the average adjacency coefficient of nodes, which is defined as the ratio of the number of nodes directly connected to an arbitrary node to the total number of nodes in the network, and by Cj(k) the set of nodes connected to node Yk at the j-th iteration step.

Thus, at the first step we have C1(k)= A(k). At the second step, the set C2(k) of nodes connected to node K will be equal to the set of connected nodes in the previous step (i.e., the set C1(k)) combined with the set of nodes that are directly connected to these nodes, i.e.:

$$C_2(k) = C_1(k) \bigcup_n A(n), n \in C_1(k) \tag{1}$$

Continuing for $j = 2,3, \dots$ we obtain the following expression for the set C_j at the j-th iteration step can be defined as follows:

$$C_j(k) = C_{j-1}(k) \bigcup_n A(n), n \in C_{j-1}(k) \tag{2}$$

where $\bigcup_n$ is the sign of the union of sets A(i), i changes from 1 to n.

We note an important property of undirected graphs. We denote by R(k,n) the relation of connectivity between nodes Yn and Yk (Chekuri et al. 2011). This relation is symmetrical because the communication channels are bidirectional. In addition, it is transitive, i.e., if the condition R(k,n) and R(n,l) are true, then R(k,l). It is also obvious that each node is connected to itself, i.e., R(k,k) is true. The presence of these three properties shows that the connection relation is an equivalence relation (Engelking 1977; Kolmogorov and Fomin 1976). In turn, this means that the entire set of network nodes can generally be represented as a set of areas, in each of which the nodes are interconnected. Nodes belonging to different areas are not connected to each other.We will call a network fully connected if all its nodes are connected, i.e., there is a path from any network node to any other. Otherwise, the network will be called partially connected. In what follows, we will only consider only a fully connected network.An important consequence of this result is that the sets Cj defined by Eq. 2 are monotonically increasing and, due to the finite number of nodes, the sequence {Cj} is bounded (Eq. 3):

$$C_1(k) \subset C_2(k) \subset \ldots \subset C(k) \quad (3)$$

where $C(k)$ is a limit set.

Therefore, the number of iterations r can be defined as follows (Eq. 4):

$$r = min\ J{:}\ C_{j+1} = C_j \quad (4)$$

The relations (2)-(4) obtained above allow, firstly, to establish the existence of a route between arbitrary nodes and, secondly, to determine all the shortest routes between these nodes. The presented algorithm is used in a simulation model to construct the optimal route between the packet source and the receiver.

METHODOLOGY

The complexity of the processes occurring in FANET does not allow the use of analytical methods to calculate its characteristics and necessitates the use of simulation modeling (Kleinrock 1976). Well-known modeling packages, such as General Purpose Simulation System (GPSS) (Schriber 1974), OPNET (Mittal 2012), NS2 (Issariyakul and Hossain 2009), and a number of others, do not fully take into account the main features of FANET, particularly the rapid variability of the network topology and the presence of dynamic routing. Therefore, the authors refined the simulation model for sensor networks, a detailed description of which is given in Borodin et al. (2023), taking into account the variability of the network structure (movement of subscribers in space), the presence of packet distortions, multiple channel access methods, and a number of other parameters.

This model consists of three functional blocks: a block for setting initial data for modeling, a modeling block, and blocks for processing and displaying simulation results.

The block for setting initial data for modeling corresponds to the Open Systems Interconnection model (OSI) and sets the values of the input parameters in all levels of this model.

At the Physical layer, the following main parameters are defined: number of network nodes; energy potentials of the radio link; number of transmission channels, methods of sealing and fixing channels; models for calculating the probability of packet distortion.

The following parameters are defined at the Link layer: access methods; packet acknowledgment methods; operation algorithms and service channel parameters.

The Network layer defines composition of metrics for packet routing, parameters of network structure changes (various mobility models for UAV), and routing methods.

The Transport layer defines structure of the transmitted messages and the method of splitting the message into packets and redundancy options for channels for data exchange between nodes.

At the layer of Application Processes are set characteristics of the message source (intensity of message flow, distribution of message size, and distribution of time between adjacent packets in a message); for each source of messages, the recipient node of the corresponding message is indicated.

The process of modeling in the modeling block is carried out by events on a given time interval of the network operation. It is possible to study stationary and non-stationary processes of network behavior with a given allowable statistical error.

The model allows determining the statistical characteristics of the following quantities: packet transmission waiting time in the node; packet transmission time over the network from the source to the consumer; packet retransmission time and number of retransmissions; probability of packet loss, etc.

The model includes mechanisms for recognition of the network transition to an unstable state, reduction of modeling time and obtaining express results, optimization of network parameters, and display during the simulation of the network parameters.

Blocks for processing and displaying modelling results form given statistics based on the obtained results (distribution laws, average values, dispersions, etc.) and display the obtained results in the form of graphs and tables.

Below there is a brief description of the main results obtained using this model: multiple access methods and the process of updating AM used to organize efficient dynamic routing in the network.

Met transmission channel between UAV

When conducting research, we will consider the following two options for multiple access to the data exchange channel between UAV: cyclic access (CA) with TDM and random synchronous access – slotted ALOHA.

In the first case, deterministic access to the channel is carried out and each UAV is allocated one time interval (slot), during which it completely transmits AM data. Time slots follow each other, with each slot assigned to one specific UAV. With random synchronous access, the channel is divided into successive slots, the duration of which is sufficient to transmit data about AM.

Each UAV randomly selects a slot to transmit AM information. If multiple UAV select the same slot, a data collision occurs and the corrupted data is not retransmitted (an uncorrupted transmission is possible on the next data transmission).

This article does not discuss the technical aspects of organizing a synchronous radio channel for data exchange between UAV, since solving this problem is the subject of a separate study.

Description of the process of updating LAM

To build an optimal route, each node must have LAM that is identical to the network (actual) AM. The algorithm for each node to form its own LAM is described below. It is assumed that the total number of nodes is N and each node has its own number in the network (from 0 to N-1).At the initial moment, each network node has its own (local) 0 LAM, i.e., all elements of these matrices are equal to 0. As information is received from other nodes, LAM is updated to fully match the network matrix. The formation of LAM is carried out as follows. An arbitrary node of YK network sends a broadcast routing message containing the number of this node. This message is received by all nodes that node YK is connected to. Each YL node that received this message updates its LAM.

In it, in particular, units appear at the intersection of the K-th column and the L-th row (L is the number of the receiving node).

Next, each node determines the change in its LAM that occurred after receiving the message from node YK. This change contains those connections between nodes that were not previously marked in LAM of the corresponding node. If the changes are non-0, then the node broadcasts a message containing LAM changes and its number.

Messages are transmitted to adjacent nodes, and this procedure is repeated cyclically. Thus, in one cycle, a message containing LAM change is transmitted from one node. In this case, nodes transmit their messages in response to an incoming message only if the received message leads to a change in their internal LAM. In accordance with the described algorithm, the process of updating matrices ends after the completion of changes to LAM.

When studying the efficiency of data transmission in FANET, the following key indicators of the LAM update process are of particular interest: share of adjacency areas – the number of nodes for which all adjacent nodes are defined in relation to the total number of nodes; share of created LAM – the number of nodes for which LAM is fully defined in relation to the total number of nodes; distribution function of the number of transmissions in which the node has completely determined LAM; and network traffic – the number of nodes transmitting LAM update messages in relation to the total number of nodes.

The next section of the article provides some numerical simulation results that allow us to assess the impact of data transmission network parameters (including the probability of data corruption) on the above indicators. It identifies areas of effective application for each of the considered access method and proposes indicators for determining whether the LAM update process has been completed.

RESULTS

Description of the process of updating LAM

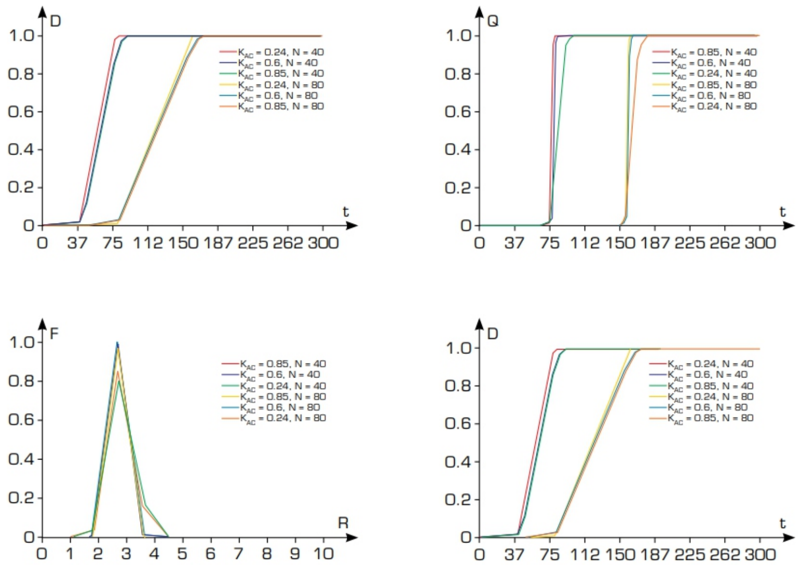
The results of modeling the process of updating matrices in the absence of distortions in the transmitted data are shown in the Fig. 1, where the following symbols are given: D is the proportion of certain adjacency areas; Q is the share of created LAM;

F is the distribution function (histogram) of the number of gears; S is the network traffic; and R is the number of gears.

Graphs depicting dependence of LAM update indicators are plotted against the current execution time of the matrix update task. As a unit of time in these and the following graphs, a time slot is selected, within the boundaries of which information is transmitted between nodes, and KAC adjacency coefficient and the number N of network nodes are parameters.

The obtained results lead to drawing an important conclusion that the number of data transmissions before a complete LAM construction is practically independent of the number of nodes and the network adjacency coefficient. As depicted in Fig. 1, the average number of gears does not exceed three, and the dispersion of the distribution of the number of gears is small and amounts to 0.1-0.2 from the average value. This allows concluding that one of the possible indicators that determine the completion of LAM update data transfers can be such a parameter as reaching a certain threshold of the number of transfers. After the LAM update is completed, the network continues to transmit data for a certain time, but this does not lead to a change in LAM. Therefore, another indicator of the completion of updating LAM is a decrease in network traffic. Additionally, the update time of LAM is an almost linear function of the number of nodes and weakly depends on the adjacency coefficient.

Figure 1 shows that for two values of N (40 and 80), the time to construct the matrix in the second case is approximately two



Source: Elaborated by the authors.

Figure 1. Change in LAM update rates over time (proportion D of certain adjacency areas, share Q of created LAM, distribution function F of the number of gears, network traffic S) in the absence of transmission distortion.

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times longer. As the calculation results showed, such a dependence of the matrix update time on the number of network nodes is also valid for other values of N.

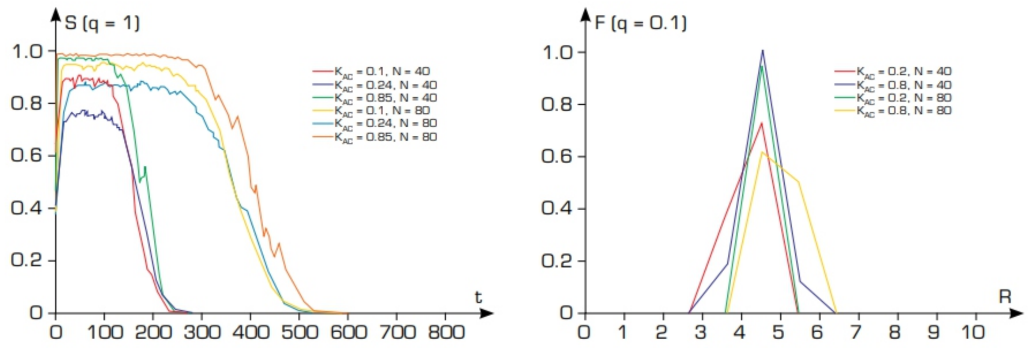
Analysis of network traffic over time shows that in the initial section all transmitted messages are significant, i.e., containing new information to update AM. This suggests that when forming AM, access via dedicated channels is effective, since it is in this case that the data transmission channels are fully loaded.

Now we consider the characteristics of updating matrices in the presence of distortions in transmitted data caused by noise and interference.

As the simulation results showed, the presence of distortions during data transmission, provided that each node transmits data about LAM only if there are changes in its LAM, leads to the impossibility of completely constructing LAM. These changes themselves are formed based on data received from other nodes. If there are no errors during transmission, then with probability one all changes will sooner or later reach all nodes. However, in the presence of distortions, there is always the possibility that any node will not receive all changes to LAM of other nodes and, as a result, will not be able to fully form its LAM.

In this regard, in the presence of distortions, it is advisable to use another mechanism for updating matrices, in which each node transmits its data regularly without taking into account changes in LAM in relation to the previous transmission. The results of modeling the process of updating matrices in the presence of distortions and using such LAM update mechanism are shown in the Fig. 2. During the simulation, the assumption was made that each message could distorted with probability q, with distortions occurring independently of each other.

The results suggest that LAM update time in the presence of distortions depends on the number of network nodes and weakly depends on the adjacency coefficient. Experiments were also carried out with the model for various values of q, which showed that the effect of interference significantly affects LAM update time and the number of transmissions before LAM is completely updated. Moreover, the greater the amount of data distortion, the greater the increase in LAM update time and the number of transmissions. In other words,



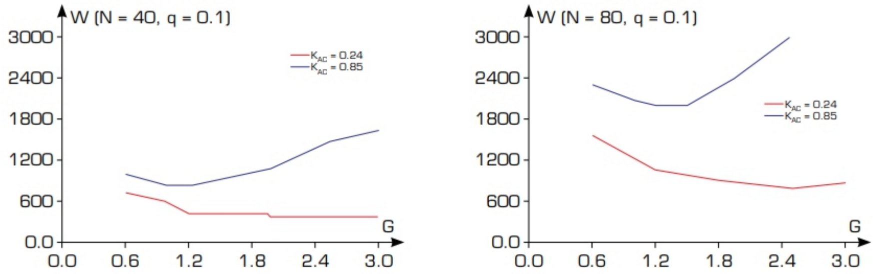
Source: Elaborated by the authors.

Figure 2. Change in LAM update rates (proportion D of certain adjacency areas, share Q of created LAM, distribution function F of the number of gears, network traffic S) in the presence of transmission distortions.

a non-linear relation can be traced, for example, when q doubles, LAM update time and the number of transmissions increase from three to five times depending on the value of q. Generally, the average number of transmissions before a complete update of LAM per node does not exceed 10, with the coefficient of variation weakly depends on the probability of distortion and does not exceeding 0.15.It should also be noted that with a high probability of corruption, a decrease in network traffic is no longer an indicator of the completion of LAM update, as was observed in the case of no corruption. LAM are formed during the entire transmission of significant messages.

Random access (RA) LAM update rates

Since in some cases the use of CA may not be possible, it is advisable to use slotted ALOHA without handshake as an alternative (Abramson 1970; Tobagi 1982). In this case, time windows (slots) are continuously transmitted over the channel, with sufficient duration for packet transmission. A network node with a packet to transmit randomly selects a slot and transmits its packet there. Since the slot selection mechanism is random, collisions may occur due to the simultaneous transmission of packets by two or more nodes in the same slot, leading to packet loss.During simulation, it was assumed that the network contains N nodes connected to each other by a duplex data exchange channel. The transmission of packets by nodes is carried out in broadcast mode without acknowledgment and each node transmits messages after a random time with an exponential distribution. The total traffic (message flow from all nodes) was assumed to be Poisson, with an intensity per slot is equal to G.Simulation results are depicted in the Fig. 3, where W is the average LAM update time normalized with respect to the duration of the time slot for data transmission.



Source: Elaborated by the authors.

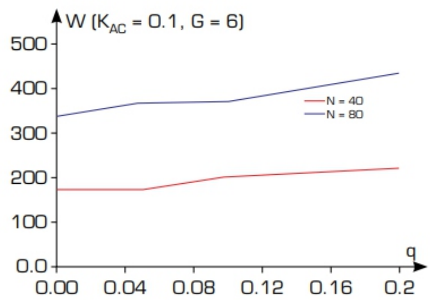
Figure 3. Change in LAM update time from the size of G of total network traffic with the RA and different number values of N (40 and 80) of network nodes.

Analysis of the results shows that LAM update time significantly depends on the value of G network traffic, while there is an optimal traffic value at which the update time is minimal. For a fixed value N of the number of nodes, as the network adjacency coefficient increases, the optimal value of traffic decreases. It should also be noted that with KAC < 1, the total traffic may well be greater than one, while network congestion is not observed.

Comparative analysis of the dependencies presented in the Figs. 1 and 3 shows that LAM update time with RA and no errors is considerably greater than the update time with CA.

It should be noted that with RA, the matrix update time decreases as the adjacency coefficient decreases. This is due to the fact that high network connectivity also means a high probability of message collision, which leads to an increase in matrix update time. This circumstance indicates that RA is advisable to use at low KAC values.

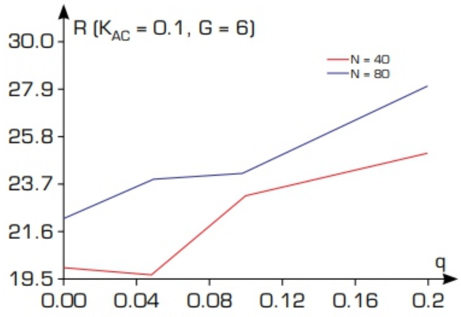
Figure 4 shows the dependence of the average LAM update time for the adjacency coefficient KAC = 0.1 on the probability of distortion for various values of N and the optimal network traffic value.



Source: Elaborated by the authors.

Figure 4. Average LAM update time versus corruption probability.

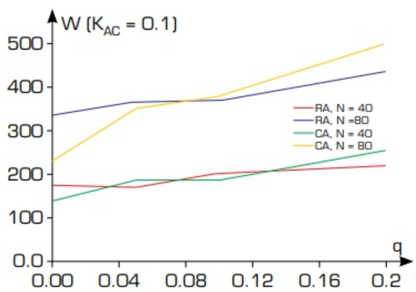
If during CA distortions significantly affect LAM update time, then RA is much less sensitive to distortions. This trend is also true for the number of transmissions for updating LAM, which is illustrated by the dependences of the average number of transmissions for RA on the value of q shown in the Fig. 5.The average number of transmissions per network node with RA (Fig. 5) significantly exceeds the similar characteristics when using CA (Figs. 1 and 2). Moreover, additional studies have shown that the coefficient of variation in the number of transmissions does not exceed 0.15 and almost coincides with this characteristic of CA.



Source: Elaborated by the authors.

Figure 5. Dependence of the average number of transmissions for LAM update on the probability of distortion at the optimal traffic value.

Also, the simulation results showed that the lower the adjacency coefficient, the smaller the difference in the characteristics of networks with RA and CA. To confirm this fact, the Fig. 6 shows the dependences of the average LAM update time for RA and



Source: Elaborated by the authors.

Figure 6. Comparative characteristics of the average LAM update time with RA and CA.

CA with the adjacency coefficient KAC = 0.1 and various values of the number of nodes and the probability of packet distortion.

A comparison of network characteristics with RA and CA shows that with a low adjacency coefficient, RA provides better performance, and the greater the number of nodes and the greater the probability of distortion, the higher the difference.

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DISCUSSION

The simulation results showed that LAM update time depends almost linearly on the number of network nodes: the more there are, the longer the matrix update procedure. As a discussion, the authors propose one of the possible options for reducing their update time through network segmentation.

The following approach is proposed. The original network is divided into P1 subnets, each of which has the same number of nodes. Each of these subnets is in turn divided into P2 subnets. Through M partitions (M is the partition depth) we obtain that each subnetwork contains N/P nodes, where P = P1 * P2 * … * PM ("*" sign means multiplication).

The process for updating AM would proceed as follows: first, the matrices of nodes included in subnets of depth M are updated; then the matrices of subnets at level M-1 are updated, etc.

The total matrix update time will be proportional to (Eq. 5):

$$t = N/P + P_1 + P_2 + \dots + P_M \tag{5}$$

The update time takes a minimum value if (Eq. 6):

$$P_1 = P_2 = \dots = P_M = \sqrt[M+1]{N} \tag{6}$$

Substituting (Eq. 6) into (Eq. 5) we obtain the following expression for the minimum update time (Eq. 7):

$$t_M = (M+1)\sqrt[M+1]{N} \tag{7}$$

The resulting expression determines the minimum LAM update time at the partition depth M. Differentiating (Eq. 7) with respect to M and equating the derivative to 0, we obtain an estimate for the optimal partition depth equal to (Eq. 8):

$$M_{ipt} = \ln N - 1 \tag{8}$$

And finally (Eq. 9):

$$t_{min} = \sqrt[\ln N]{\mathrm{N}} \ln N = \mathrm{e} \ln N \tag{9}$$

The obtained result shows that in this case the dependence of the update time is a logarithmic function of N, i.e., depends much less on the number of nodes than in the absence of segmentation.

As directions for further research into the efficiency indicators of routing methods in self-organizing networks, the authors consider it relevant to solve the following problems: assessment of the impact of failure of individual network nodes on its connectivity and, accordingly, on the time of updating routing information; development of routing algorithms and assessment of routing quality with partial correspondence of LAM to the network AM; development of methods for generating
AM taking into account the actual route traveled by the packet from the source to the location; assessment of the influence of the speed of node movement on LAM update time; assessment of the influence on the network characteristics of the characteristics of radio wave propagation in various environments and in the presence of screens (opaque or translucent).

CONCLUSION

The article studies the characteristics of updating LAM in FANET, the presence of which allows each UAV to autonomously form message transmission routes. An approach is proposed to the formation of LAM in the process of multiple exchanges between UAV, which are FANET nodes.

To assess LAM update performance, a simulation model has been developed that adequately reflects such main features of FANET, such as high UAV mobility and the rate of change in network topology, the presence of dynamic routing, multiple channel access methods, and a number of other parameters.

An analysis of FANET characteristics was carried out using two mechanisms for accessing a common data transmission channel in the process of updating matrices: deterministic (CA) and RA. For these two access methods, the behavior of the network is considered in the absence and presence of distortions in transmitted messages.

As follows from the simulation results described in the Results section, with CA and no distortion, the update time of local matrices is an almost linear function of the number of nodes and weakly depends on the adjacency coefficient. In the presence of distortions, LAM update time depends on the number of network nodes and weakly depends on the adjacency coefficient. Moreover, with an increasing q of message distortion, a nonlinear increase in LAM update time and the number of transmissions is observed.

It also follows from the simulation results that with RA and no errors, LAM update time is considerably longer than with CA.

The presence of distortions leads to deterioration of network characteristics (increase in time and number of transmissions for updating LAM) with RA, although this tendency does not appear as sharply as with CA.

A comparative analysis of modeling results for cyclic and RA has shown that in the absence of distortions (or with a small amount of distortion), CA provides higher efficiency compared to RA. RA is advisable to use with relatively high probabilities of data corruption (of the order of 0.1 and above), a numerous nodes (more than 40) and low network connectivity.

One of the important results of the work is the identification of indicators (reaching a certain threshold of the number of transmissions, reducing the level of network traffic), by which one can judge the completion of the LAM update process. However, this statement is true mainly for CA with a sufficiently small amount of message distortion.

An option has been proposed to reduce the update time of LAM through FANET segmentation, which is especially effective with a numerous network nodes.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Borodin V, Kolesnichenko V, and Kovalkina N; Methodology: Borodin V, Kolesnichenko V, and Kovalkina N; Software: Borodin V, Kolesnichenko V, and Kovalkina N; Validation: Borodin V, Kolesnichenko V, and Kovalkina N; Formal analysis: Borodin V, Kolesnichenko V, and Kovalkina N; Investigation: Borodin V, Kolesnichenko V, and Kovalkina N; Resources: Borodin V, Kolesnichenko V, and Kovalkina N; Data Curation: Borodin V, Kolesnichenko V, and Kovalkina N; Writing - Original Draft: Borodin V, Kolesnichenko V, and Kovalkina N; Writing - Review & Editing: Borodin V, Kolesnichenko V, and Kovalkina N; Visualization: Borodin V, Kolesnichenko V, and Kovalkina N; Supervision: Borodin V, Kolesnichenko V, and Kovalkina N; Project administration: Borodin V, Kolesnichenko V, and Kovalkina N; Funding acquisition: Borodin V, Kolesnichenko V, and Kovalkina N.

DATA AVAILABILITY STATEMENTAll

data sets were generated or analyzed in the current study.

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