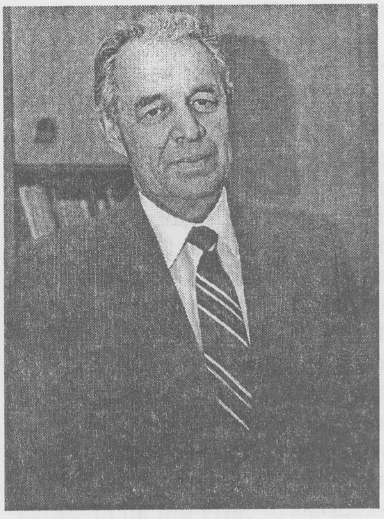

# SCIENTIFIC AND ORGANIZATIONAL WORK OF ACADEMICIAN ALGIRDAS ŽUKAUSKAS AND HIS THERMAL PHYSICS RESEARCH ACTIVITIES IN 1947–1997

Engineering and scientific research workers were greatly needed in Lithuania for technology development, as industry and energy sector began to grow after World War II. In 1945 the technical departments of Kaunas Vytautas Magnus University began to prepare young specialists and among them those in thermal engineering. Among the graduates of 1947 A. Žukauskas alone became Dr. habil., Academician and Professor.

Although he stayed to lecture at the then University, he continued to dream of scientific research, and when he saw in a press publication that MEI (Moscow Energy Institute) announced admission to doctorship studies, he visited MEI, acquainted himself with research done there and came to know outstanding researchers and creators of those times in thermal physics and power engineering, professors M. Mikheyev, M. Vukalovich and M. Styrikovich. With them he planned his research course and line to which he later dedicated his whole life.

In the beginning of the 20th century the similarity theory was created and used in practice, including generalizations of some laws of heat exchange processes. Due to it, investigation results of heat exchange in various systems may be expressed by simple formulas using the similarity criteria which encompass the parameters describing physical properties of fluids at corresponding temperatures. At the end of the 50s such generating criteria were few. Even in the simplest case of cross flow past the cylinder the main results were obtained using thin wire and a cylinder for the flow of air, and laws for water, oil and other flows, including high temperature gas flows, remained unknown.

After receiving solid scientific and moral support and being acquainted with laboratories, experimental equipment and measuring devices of MEI and G. Krzhyzhanovsky Power Engineering Research Institute (ENIN), A. Žukauskas built an aerohydrodynamic experiment rig, the first in this country. It was situated in Mechanics Faculty (Gediminas- K. Donelaitis Str.) of Vytautas Magnus University, Kaunas. The rig enables to place a cylinder into a cross flow of openly circulating (blown by fan) air or a looped flow of hot or cold water driven by pump and not only to measure heat transfer, but also to assess the influence of different properties, at different temperatures, of ambient water and air.

For the use of the so-called Prandtl number Pr for mean heat exchange in criteria equation $\mathrm{Nu}_f = c\mathrm{Re}^n\mathrm{Pr}^m(\mathrm{Pr}_f/\mathrm{Pr}_w)^p$, not only its power index $m$ was determined, but also, for the first time in the history of heat exchange science, the power index $p$, evaluating direction of heat flux in case of outer flow, *i. e.* if heat flows from the hotter cylinder surface to a colder fluid or, *vice versa,* hotter fluid transfers heat to the colder surface of the cylinder. For air flow $\mathrm{Pr} \approx 1$. Investigations using liquids enabled to increase considerably the domain of variation of the Re number and at the same time to define more exactly its power index $n$, which increases as Re increases from 0.4 at $(1 < \mathrm{Re}_f < 50)$ and 0.5 at $(50 < \mathrm{Re}_f < 10^3)$, 0.6 at $(10^3 < \mathrm{Ref} < 2{\cdot}10^5)$ and 0.8 at $(2{\cdot}10^5 < \mathrm{Re}_f < 10^7)$. Initially, the first two Re values were obtained for small Re interval, later, after several years of research, these values were extended to the magnitudes mentioned.

For average heat transfer of cylinder, the initially determined value of the power index $m$ of Pr number was 0.37. Later, when local heat exchange at the critical point around the cylinder was investigated, laminar and turbulent areas of flow around the cylinder were detected with their specific $n$ and $m$ values ($n$ = 0.33, 0.5 and 0.8; $m$ = 0.33 and 0.43). These hypotheses were incentives for A. Žukauskas to carry out an investigation of longitudinal flow over a flat plate by laminar or turbulent viscous liquids. In this way foundations were laid for calculations of heat transfer of the mentioned cylindrical and flat surfaces for all cases encountered in practice.

Under the leadership of Prof. A. Žukauskas, investigations of his followers have shown that in the case of laminar flow, due to very low mixing of particles in the boundary layer, heat exchange processes differ from the turbulent ones: not only power indexes in criterial formulas are different, but also the way the plate surface temperature varies and the length of the unheated front part of the plate have a great influence upon the expression of heat exchange.

This influence was not found in the case of turbulent boundary layer because of good mixing of particles with different temperatures, and this was confirmed later by calculations.

The results obtained prompted investigations of local heat exchange along the perimeter of the cylinder. Heat transfer processes on the rear side of the cylinder with flow separation are more complicated. To solve this issue, A. Žukauskas organized special large-scale investigations, the results of which were crowned by an official Discovery Award, the second in Lithuania.

A single cylinder is not often found in industry and power equipment, usually main domains of heat exchangers are in-line and staggered bundles of tubes in crossflow, so the further attention of A. Žukauskas was dedicated to them.

After detailed investigations of bundles of tubes at various geometries very significant results for a wide interval of Pr number (1–10 000) were obtained and added to the classic knowledge stock of modern thermal physics.

Later the investigations of bundles of tubes were supplemented with investigations of cylinders of rectangular cross-section in crossflow, having fins of various forms, and local heat transfer. These investigations were prolonged after the experimental rig was removed from the University and mounted in one of the laboratories of the former Institute of Physical-Technical Problems of Energetics of the Lithuanian Academy of Sciences, where the same ideas were applied. Later, additional laboratories were established with powerful experimental rigs with circulating flows of air, water, transformer oil and glycerol. One rig pump had the power of even 600 kW. The total power of experimental rigs of the newly built experimental laboratory building reached 12 MW. Few research organizations could boast of such laboratories, at least in the former Soviet Union there was none.

These experimental facilities were useful for the continuation of further theoretical and applied research of heat transfer, its intensification and control. Much attention and care was given by Prof. A. Žukauskas to heat exchange intensification and development of compact heat exchangers, small in volume and large in heat exchange area.

Along with heat exchange measurements, consequent and exact measurements of hydraulic drag were carried out and criteria of heat exchanger efficiency were established while determining the conditions at which maximum heat transfer with minimum hydraulic drag is obtained.

To evaluate heat exchangers efficiency and reliability in addition to hydraulic losses, also assessment of their element vibrations had to be made. On the other hand, little was known about the influence of vibrations on heat exchanger durability. Large-scale investigations by A. Žukauskas and his disciples led to the determination of dangerous limits as well as desirable intervals within which heat exchange increases several times due to vibrations.

The results of investigations in the wide interval of the Prandtl number (1–1000) for Prof. A. Žukauskas were incentives to further heat transfer investigations. And then came the era of cosmic ships, rocket assemblies and magnetohydrodynamic generators, where high rates of heat exchange take place at high temperatures, so the laws earlier established could not be applied.

For the solution of this problem Dr. J. Stasiulevičius, a disciple of Academician M. Styrikovich, after his doctorship course in Moscow chose a new and urgent for those times research direction – the case when heat is transferred from element wall surfaces heated to 1000 K to a colder gas flow at various pressures. This problem was very urgent at that time for the development of small gas-cooled nuclear plants of (as it appeared later) cosmic vehicles. It was important to replace the parameter $(\mathrm{Pr}_f/\mathrm{Pr}_w)^{0.25}$ as not suitable for gas flow, to consider the influence of geometry factor and of gas pressure, which gives rise to great Re values (up to $10^8$) upon heat transfer. These investigations prove that in the case of hot wall surface and cold gas stream ($0 < T_f/T_w < 1$) it is sufficient to use the ratio $(T_f/T_w)^{0.25}$ instead of $(\mathrm{Pr}_f/\mathrm{Pr}_w)^{0.25}$.

Results of investigations of heat transfer from hot surfaces to gas flows with temperature factor assessment gave rise to the necessity to check its suitability for the cases of cold wall and hot gasflow ($1 < T_f/T_w < 10$). Most researchers (*e. g.* Prof. B. Petukhov) automatically interpolated these formulas leaving the same ratio $(T_f/T_w)^{0.25}$. Later Prof. A. Leontiev and others doubted that hypothesis, therefore in 1963 Prof. A. Žukauskas decided to confirm or to reject it on the basis of detailed experiments.

After creation of laboratory of high temperature two-atom gas flows with powerul electric arc heaters (plasmatrons), it was possible to establish that in this case the ratio $T_f/T_w$ is not necessary, as the power index is 0. So, due to Prof. A. Žukauskas foresight, after long and very costly high temperature experiments, another gap in heat transfer science was filled: temperature ratio $(T_f/T_w)$ within the interval from 0.1 to 10 was evaluated in logarithmic coordinates not by the interpolating line, as it had been thought before our investigation, but by a curve including coordinate intersection point $(\mathrm{Nu}_f/\mathrm{Nu}_w)$ – $(T_f/T_w)$. One the left side ($1 < T_f/T_w$) it is evaluated by a ratio

$(T_f/T_w)^{0.25}$, on the right side ($T_f/T_w > 10$) – by a horizontal line. Later exact calculations involving the elliptic equations system ideally confirmed these results. This is valid also for dissociated two atom gases, when their physical properties (more than 2500 K for air and more than 4000 K for nitrogen) are calculate according to "frozen" conditions.

Investigation of multiatomic gas and combustion product dissociation and radiation processes was carried out for many years in natural gas combustion experimental rigs and in the elements of the Stirling engines. The same rigs were also used for investigations of high temperature fracture of materials, as many heat transfer processes, for example in magnetohydrodynamic generators, coexist with mass transfer. Results obtained at that time were urgently needed for cooperation with the High Temperatures Institute of the former USSR Academy of Sciences. The Institute had been developing a heat power plant functioning according to this principle. There were also hopes to use it in Lithuania and so to save large amounts of fuel oil.

Investigation of complex heat exchanges with chemical reaction enabled to create an engine-pump working on solar energy and used to pump water in remote areas without electricity far away from power plants.

As may be seen from his vast and expedient research scope, Prof. A. Žukauskas carried out enormous scientific-organizational work directing Lithuanian Energy Institute, its Scientific Council and later the Lithuanian Committee for Science and Technology, for many years being a Vice-president of the Lithuanian Academy of Sciences, also the Chairman of Technical Sciences Department of the Lithuanian Academy of Sciences.

Under the leadership of the Committee of Science and Technology of Lithuanian Republic, the Electrification Program of the Lithuanian Republic was intensely carried out and industry expanded. His connections with the largest institutes of the former Soviet Union and bęst known scientists were useful for implementing Elelctrification Program of the Republic of Lithuania, building new electric power plants and new power transmission networks. While implementing this program, Prof. A. Žukauskas had close ties with regional and all-union planning and development organizations and their leaders, those ties being scientific and organizational. All this helped him to obtain better conditions for Lithuania. His words were weighty, as his efforts being Chairman of Committee of Science and Technology greatly influenced the development of the Lithuanian energy sector. At the same time Lithuanian industry was developed, decentralizing it throughout the whole territory, expanding new regional centres without concentrating it in the main cities. To ensure normal development of these new centres, a highway system net was developed. In addition, ethical problems of workers were successfully solved across the Republic.

This enormous scientific-organizational work required a lot of creativity and inventiveness, large funds, highly educated staff, close and vast relations with scientists all over the world, many of whom visited our laboratories and conferences, where they read their reports and took interest in our investigation results. Prof. A. Žukauskas was a welcome guest in foreign scientific centres, as well as his followers who are also frequently invited at present.

Results of Prof. A. Žukauskas' scientific and organisational activity require a long time to be listed or named. When in 1953 prof. A. Žukauskas was elected Director of the Physics and Technology Institute of the Lithuanian Academy of Sciences, under his supervision investigations in the fields of power engineering, metal technology, building and architecture, agricultural engineering and electrification, textiles and technical physics were initiated. On the basis of this institute in 1956 four new independent institutes were founded, among them the Institute of Energy and Electrical Engineering. In the institute Prof. A. Žukauskas for the first time organized scientific research in the field of thermophysics, and for several years was the Head of Thermal Laboratory Engineering, later renamed Laboratory of Thermophysics. In 1967 it was reorganized into the Institute of Physical and Technical Problems of Energetics (since 1992 Lithuanian Energy Institute). Later it became one of the largest multibranch scientific centres belonging to the Lithuanian Academy of Sciences. Prof. A. Žukauskas as the scientific leader of this Institute devoted most of this efforts to creating the basis of experimental facilities, acquiring modern measuring devices and rallying harmonious association of scientists for solution of urgent power and fundamental thermophysical problems. The institute gained a wide international recognition due to outstanding and vivid works in these fields. The aforementioned institutes became well-known world science centres, their research results glorifying Lithuanian science.

Besides fundamental and applied research work carried out upon contracts with many world science centres and organizations, careful preparations were made for practical design and production activity. Near the Institute a multistore building for designers with a one-store production base was built, and a unique 80 work place scientific and maufacture shop was erected. Also, a powerful air compressor facility, an oxygen-nitrogen supply station and a computational centre were established. Not far from Kaunas, on a 20-hectare site, a factory manufactruing heat exchangers was intended to be built. However, it was not implemented in due time.

In 1966 A. Žukauskas was elected Vice-president of the Lithuanian Academy of Sciences, and he fruitfully worked in this position for more than 25 years. In 1992 he became Chairman of the Department of Technical Sciences of the Lithuanian Academy of Sciences and performed with characteristic energy, inventiveness and carefulness until his tragic death.

Prof. A. Žukauskas, the founder of the Lithuanian school of heat transfer and thermal physics, much of his attention devoted to ecological and thermoaerohydrodynamic problems of main power facilities, cooling reservoirs and ponds of the Ignalina NPP and Lithuanian power plant, initiated and supported solutions of these problems. In the last several years he investigated and generalized heat transfer intensification and heat exchanger efficiency enhancement laws as well as the influence of power facilities and other enterprises upon environment and considered atmospheric pollution by combustion products and "greenhouse effect" problems.

Convective heat transfer laws and formulas discovered by A. Žukauskas are suitable for various applied engineering calculations, the methods proposed by him are widely applied for designing heat exchangers for power industry, chemical, food product industry branches, *etc*. Results obtained by him and his colleagues are included into many textbooks of higher schools in many countries and main special handbooks which, as the analysis shows, come to more than 80 fundamental editions.

With co-authors and alone Acad. A. Žukauskas published over 550 scientific articles, 170 of them in English, German, Chinese and other languages in various foreign editions. Numerous other publications on science organization and popularising, public affairs, scientific reports, interviews, summaries were written by him.

He is the author of 15 well-known monographs published in Russian, English and Chinese. Among them "Heat transfer in laminar fluid flows" (1969), "Heat transfer in turbulent fluid flows" (1973), "Heat transfer of a cylinder in crossflow" (1979), "Heat transfer in the banks of tubes in crossflow" (1968, 1986), "Hydrodynamics and vibrations of tube bundles in crossflow" (1984), "High-performance single-phase heat exchangers" (1982) and others.

Prof. A. Žukauskas was founder, constant administrator and editor-in-chief of the monograph series "Thermophysics". The first book was published 30 years ago. 25 books of this series were published and 11 of them were translated into English and published in U. S. A. In addition, he was editor of many international journals or member of their editorial boards. Among them journals of the Lithuanian Academy of Sciences "Power Engineering", "Science and Tecnology", "International Journal of Heat and Mass Transfer", "Achievements in Heat Transfer", "Enhanced Heat Transfer" (editor for European countries). He was an editor of "Heat Exchanger Design Handbook" and "Heat Exchanger Design Update" popular among thermal physics professionals and engineers. He made a considerable contribution into international co-operation between heat transfer scientists and worked successfully in various committees of power engineering and heat-and-mass transfer in Lithuania, the Baltic States of the Soviet Union and other countries. For many years he took part in the work of the World Assembly of Heat Transfer Conferences, the International Heat-and-Mass Transfer Centre in Yugoslavia, the International Hydraulic Association, the Committee of Heat Transfer of Baltic States, Heat-and-Mass Transfer Committee of the former Soviet Union. Prof. A. Žukauskas was widely known among heat transfer professionals, and the work carried out under his leadership is a significant contribution into thermohydrodynamic and heat exchanger theory. Fruitful work has been done also in power engineering: for many years he led Lithuanian Permanent Power Development and Atomic Energy Commissions and directed the preparation of prospective plans for Lithuanian economy and power industry.

Prof. A. Žukauskas is the author of one Lithuanian Scientific Discovery and of 13 inventions. Under his guidance and with his help over 50 Doctor of science theses were maintained, among them 10 Hab. Doctor Theses. Most of his followers fruitfully continue the investigations initiated under his leadership. He was also awarded the National Prize in Science and Technique (1975). He was Member of Institution of Mechanical Engineers (UK) (1992) and Member of the Russian Academy of Natural Sciences (1994).

World heat transfer science and the Lithuanian energy sector and power industry suffered heavy loss because of the tragic death of Acad. A. Žukauskas. His strategic thinking and his foresight of key directions, use of world information and close ties with scientists all over the world created conditions and possibilities to lead in may fields of research. He made Lithuania famous by his erudition, published books and articles and opened doors to all research centres in the world for his students and followers.

Merits of Acad. A. Žukauskas to the world and Lithuania are above valuation; criteria laws of heat-and-mass transfer and hydraulic losses established by the association led by him became classic works of the world. They are included into most outstanding international handbooks and textbooks and will be always useful for the design of efficient, compact and ecological heat exchangers. His works brought fame to Lithuanian science in the world.

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