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New Acoustic Devices Based on Thermoacoustic Energy Conversion

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1. INTRODUCTION

A rich variety of thermoacoustic phenomena arises from thermal interactions between acoustic waves and a passage wall of tiny flow channels with temperature gradients[1-3]. When a steep longitudinal temperature gradient is made along a flow channel, a gas column in it spontaneously begins to oscillate at the resonance frequency[4]. Furthermore, when the acoustic wave runs through differentially heated flow channels, the acoustic intensity is thermally amplified and damped depending on the sign of the temperature gradient[5, 6]. On the other hand, acoustic waves enable us not only to enhance the heat transport from hot to cold[7, 8], but also to pump heat from cold to hot[9-11]. Since the acoustic intensity in ordinary conversation is only on the order of 10^{-4} W/m^2, one might think that acoustic waves could not carry a large amount of energy. However, acoustic intensity can become significantly large for an acoustic wave in a tube. Indeed, acoustic intensities exceeding 100 kW/m^2 have been generated in an acoustic resonance tube by using spontaneous gas oscillations[12].

Recently, a large number of new acoustic devices based on these thermoacoustic phenomena has been developed. They are called as pistonless Stirling prime movers and coolers, since the energy conversions similar to the Stirling cycle are executed by acoustic waves instead of mechanical pistons. The innovation of pistonless Stirling engines has begun. In order to understand these new heat engines using acoustic waves, energy flows of work flow and heat flow have been proposed as basic concepts instead of work and heat[1-3]. In this article, we briefly introduce energy flows due to acoustic waves, and show our recent experimental results on the thermoacoustic engine.

2. THERMOACOUSTIC PHENOMENA

Thermoacoustic phenomena can be regarded as a result of mutual energy conversions between work flow and heat flow. Here the work flow denotes the dynamic power flow, which is equivalent to the acoustic intensity used in acoustics. Since the literature on thermoacoustics uses the term “work flow” rather than “acoustic intensity” to emphasize the contrast with heat flow, we also use work flow in this article.

2.1 Regenerator as a heart of the engine

Essential components of thermoacoustic engines are schematically illustrated in Fig. 1. A regenerator, hot and cold heat exchangers are inserted in a relatively wide tube. Tightly piled stainless-steel screen meshes, and honeycomb ceramic catalysts are often used as regenerators. A stack of thin plates is also used as a regenerator. When the acoustic wave passes through the regenerator, thermoacoustic energy conversions take place as a result of the heat exchange process between oscillating fluid in the acoustic wave and the solid channel walls in the regenerator.

The heat exchange process is characterized by a non-dimensional parameter $\omega\tau$ [1], where ω is an angular frequency of the acoustic wave, and $\tau=r^2/(2\alpha)$ represents a thermal relaxation time given by the thermal diffusivity α of the oscillating fluid and a characteristic transverse length r of the flow channel. The parameter $\omega\tau$ is related to the thermal boundary layer thickness δ of the fluid as

$$\omega\tau=(r/\delta)^2. \tag{1}$$

When $\omega\tau >>\pi$, the gas motion becomes isentropic. This holds for the adiabatic acoustic wave in a wide tube outside the regenerator, hence no energy conversion takes place. On the other hand, if $\omega\tau<<\pi$, the gas in the channel instantaneously exchanges heat with local walls in contact with it. This is because the flow channel is completely filled up with the thermal boundary layer. The gas oscillation b ecomes thermodynamically

irreversible near $\omega\tau\sim\pi$ due to incomplete heat transfer to the wall. The regenerator with $\omega\tau$ ranging from 0.1 to 10 are often used to facilitate the thermoacoustic energy conversions.

One can easily demonstrate thermoacoustic spontaneous gas oscillations[3]. If we keep the one end of the regenerator at room temperature, a loud sound is produced by heating the other end up to about 200~300 ˚C. In the spontaneous gas oscillations, the axial heat flow from the hot to the cold ends of the regenerator is converted to acoustic work flow. On the other hand, in thermoacoustic coolers, acoustic wave produces the heat flow from cold to hot ends through the regenerator. Even though the operating frequencies (~1 Hz) are much smaller than that of the acoustic devices, regenerative refrigerators such as Stirling coolers and pulse tube refrigerators also constitute thermoacoustic coolers, in which oscillatory flows driven by compressors and pistons perform the energy conversions in their regenerators. In the following, we present these energy flows in terms of acoustic variables.

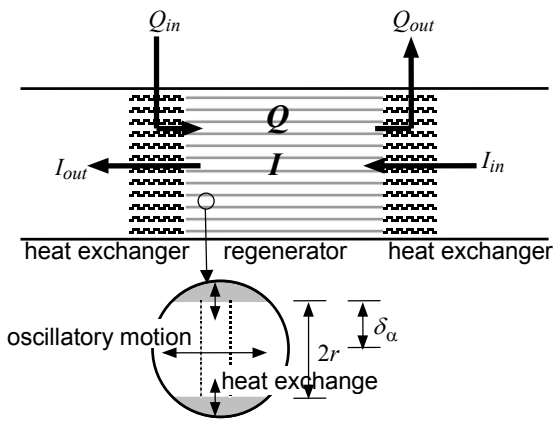


Fig.1 Essential components in thermoacoustic phenomena. Thermal contact between oscillating fluid and solid walls produces heat flow and work flow.

2.2 energy flows due to acoustic waves

Suppose a gas parcel with a unit mass is oscillating at the angular frequency ω in the fluid channel shown in Fig. 1. Acoustic pressure $P=p\cos\omega t$ can be safely assumed to be independent of the radial coordinate, since the wavelength of the acoustic wave is much larger than the transverse length of flow channels. The axial acoustic particle velocity of the gas parcel depends on the radial coordinate because of viscosity. To avoid the complexity, we use the cross-sectional mean velocity $U=u\cos(\omega t+\phi)$ so that the further discussion is made in a one dimensional system. The cross-sectional velocity U is rewritten as $U=u\cos\phi\cos\omega t-u\sin\phi\sin\omega t$. We call $u\cos\phi$ as traveling wave component of U, and $u\sin\phi$ as standing wave component of U. These are named after the phasing between P and U in well-known plane traveling and standing waves, respectively. Similarly, we also use the term "traveling wave phase" indicating that P and U are in phase, while "standing wave phase" when P and U are out of phase by 90˚. The phase angle between P and U plays a very important role in understanding the thermoacoustic energy conversions, as we see later.

The total energy flow due to the gas parcel is given by the sum of work flow I and heat flow Q as

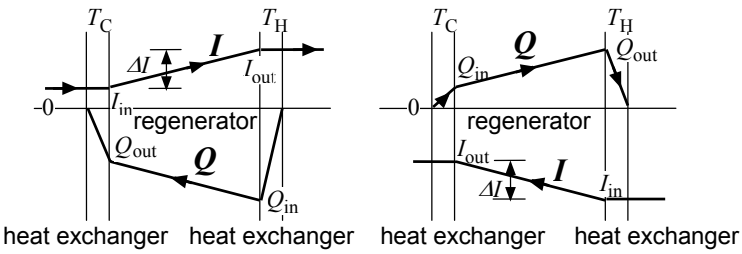
$$I+Q=\langle PU\rangle_t+\rho_m T_m\langle SU\rangle_t\,, \tag{2}$$

where ρ_m, T_m and S indicate, respectively, the mean density, the mean temperature and entropy variation about its mean value, and $\langle\ \rangle_t$ represents the time average of the quantity inside of it. Heat flow Q is proportional to the entropy flow $\rho_m\langle SU\rangle_t$. It is clear from this definition that the entropy flow is naturally zero, when $\omega\tau\gg\pi$, since the gas parcel always experiences adiabatic process (S=0). The heat exchange process between the gas parcel and a solid wall is essential in producing the axial entropy flow. How the axial entropy flow is induced by the oscillating gas parcel is intuitively illustrated in terms of a "bucket brigade of entropy" [1-3]. By calculating the time average in the definition of I, one see that $I=0.5pu\cos\phi$. This shows that only the traveling wave component $u\cos\phi$ contributes to I. Furthermore, by multiplying the cross sectional area A, we see $AI=f\oint P\cdot Audt=f\oint PdV$, where f is the frequency. This represents that I is proportional to the PV work given by an enclosed area of pressure P and the swept volume V of the oscillating piston.

Next we consider the axial distribution of energy flows. We assume that the system is thermally isolated except for hot and cold heat exchangers. Hence, the first law of thermodynamics (energy conservation law) states that

$$\nabla(Q+I)=0\,, \tag{3}$$

where ∇ represents the axial derivative. This equation assures the mutual energy conversion between Q and I. Figures 2(a) and (b) schematically shows the energy flows in a prime mover (a) and a cooler (b), respectively. The axial coordinate is taken from cold to hot. The direction of the energy flow is represented by its sign. For the prime mover, the hot heat exchanger on the right side absorbs heat power from the outside of the system, and hence the heat flow Q increases there. The heat flow Q runs from hot to cold (from right to left) in the regenerator. The difference $Q_{out}-Q_{in}$ results from the energy conversion. At the end the cold heat exchanger, the heat flow Q becomes zero, which represents that the heat power is emitted to the outside of the system. The heat



(a) prime mover (b) cooler

Fig.2 Axial distribution of energy flows in a prime mover (a) and a cooler (b). The sign of energy flows represents their direction.

flow Q is absent in the wide tube outside the heat exchangers and a regenerator, since $\omega\tau$ is very large there. However, the work flow I is present there and runs through the regenerator from cold to hot ends. As can be seen by integrating eq. (3) over the length of the regenerator, the increase of I along the regenerator is given by $\Delta I = I_{out} - I_{in} = Q_{out} - Q_{in}$. This represents the output power of the prime mover. In the cooler shown in Fig. 2(b), the work flow I runs through the regenerator from hot to cold, and as a result, the heat flow Q running in the opposite direction is produced. The cooling power is represented by the heat flow Q_{in} at the cold end of the regenerator. For a prime mover, the efficiency is given by $\Delta I/Q_{in}$. Also, the efficiency for the cooler is given by $Q_{in}/\Delta I$. An efficiency of 30% has been reported in the thermoacoustic energy conversion device[12], which is comparable to conventional internal combustion engines and Stirling engines. We show next how such energy conversion is executed by an acoustic wave by using experimental data.

3. EXAMPLES OF THERMOACOUSTIC DEVICES

3.1 Experimental method

In the acoustic field associated with the thermoacoustic phenomena, pressure, velocity, temperature and density of the gas oscillate in time at the angular frequency ω. Thus, it is important to determine the phase relation of these quantities together with their amplitudes. We simultaneously measure the pressure and velocity by using small pressure transducers and laser Doppler velocimeter, respectively[4, 13].

3.2 Thermoacoustic Stirling prime mover and cooler

We have built a thermoacoustic Stirling prime mover consisting of a looped tube having a regenerator inside and a resonator with a buffer tank, which is schematically shown in Fig. 3. Both of the loop and resonator are made of 40 mm inside-diameter pipes. The average length of the loop is 1.18 m, and that of the resonator is 1.04 m. One bar air is used as a working fluid. We have used a 40 mm long regenerator piled up with many stainless steel screen mesh (mesh size of #40). When the hot end temperature T_H exceeds 210˚C, the gas column in the apparatus starts to oscillate at the frequency of 40 Hz. By increasing T_H, it is found that the pressure amplitude of the induced acoustic wave has reached 10 % of the mean pressure.

Through the measurements of pressure and velocity along the loop and the resonator, we have found that the acoustic field resembles that of the fundamental oscillating mode of the pipe with one end closed; the velocity node is formed near the cold end of the regenerator and the pressure node is formed at the tank. Figures 4(a) and (b) respectively show the axial distribution of the phase angle ϕ of the cross sectional mean velocity U relative to pressure P, and the work flow I. Here we defined I as $A\langle PU\rangle_t$, where A indicate the cross-sectional area of the loop and resonator. The positive value of I represents that the work flow travels around the loop in the anticlockwise direction. Thus, I passes through the regenerator from cold to hot ends running up the temperature gradient. We see that the work flow I is amplified in the regenerator, which results from the thermoacoustic energy conversion. The increase ΔI represents the output power of the prime mover. The negative slope of I outside the regenerator represents energy dissipations due to viscosity and heat conduction. The output power ΔI is used to maintain the acoustic field.

To see the mechanism of the energy conversion, we focus on the gas parcel within the regenerator. As shown in Fig. 4(a), the phase angle ϕ=20˚ in the regenerator, which is close to a traveling wave phase. We illustrate the gas motion with a traveling wave phase on a pressure P versus displacement ξ diagram in Fig. 5. The gas parcel traces a clockwise ellipse on a P-ξ diagram. The enclosed area by the ellipse gives the work flow I by multiplying the frequency f. Ensuring that the gas parcel maintains a good thermal contact with the regenerator because of a small $\omega\tau$, let's consider the thermodynamic process that the gas parcel experiences in one cycle. T he gas parcel experiences "compression" in a-b, since pressure increases. The gas is isothermally heated by the wall with a positive

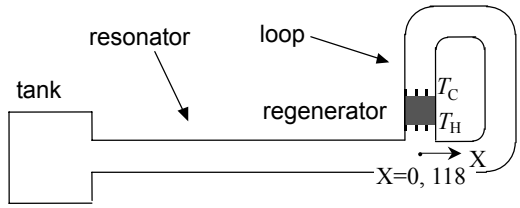


Fig.3 Thermoacoustic prime mover consisting of a loop and a resonator. The axial coordinate X is taken anticlockwise in a loop, and toward a tank in a resonator.

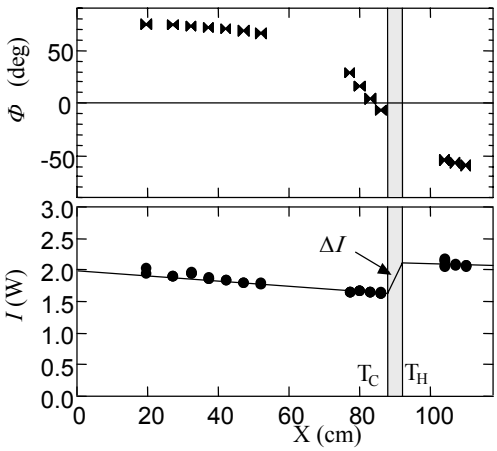


Fig.4 Axial distribution of the phase ϕ and flow I in a loop. A gray region represents the regenerator.

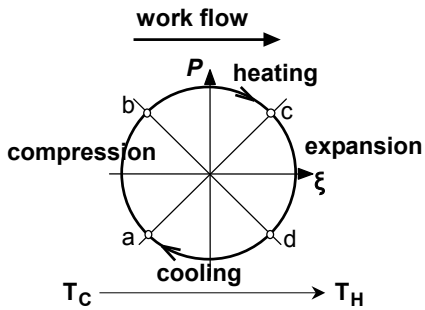


Fig.5 Pressure versus displacement diagram for the gas parcel with a traveling wave phase. For a standing wave phase, the gas parcel traces a titled straight line instead of an ellipse.

temperature gradient in b-c, due to the displacement in the channel with a small $\omega\tau$. Similarly, the gas experiences "expansion" in c-d, and "cooling" in d-a. As a result, the gas parcel with a traveling wave phase repeats a cyclic motion consisting of compression-heating-expansion-cooling. This is a similar thermodynamic cycle to the Stirling one[14]. In the conventional Stirling engines, one needs two opposed solid pistons oscillating in the same frequency but with different phases. On the other hand, the thermoacoustic engine shown in Fig. 3 performs energy conversion using a gas parcel with a traveling wave phase. However, since both of them rely on the Stirling cycle in the energy conversion, the high efficiency of 30% achieved in a thermoacoustic Stirling engine is a natural result[12]. The experimental data in Fig. 4(a) shows that the phase is about −20˚ in the regenerator. Y. Ueda[10] has shown the detailed discussion of the experimental results including the axial distribution of the amplitude.

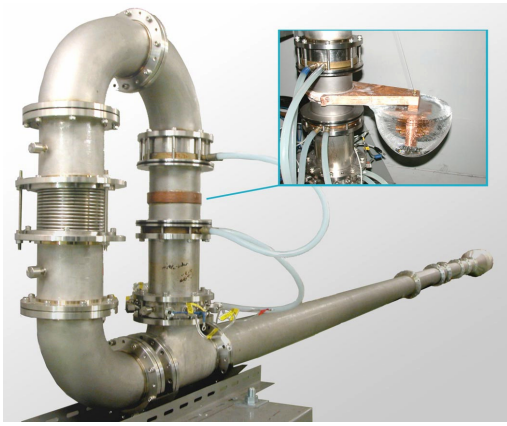


Fig.6 A large scale thermoacoustic Stirling cooler. The inset shows the ice produced by it.

Thermoacoustic Stirling cooler is possible in the same way as a conventional Stirling cooler using the reversed Stirling cycle. We installed another assembly of a regenerator and two heat exchangers into the thermoacoustic Stirling prime mover shown in Fig. 3. One end of the regenerator, from which the work flow I runs into the regenerator, was kept at room temperature. We found that the other end of the regenerator was cooled by 16˚C from room temperature. In order to improve the cooling performance, we replaced the working gas from one-bar air to pressurized gas mixture of He and Ar, and obtained a lower temperature of −25˚C[15]. This cooler has no moving parts nor Freon gas. Based on the experimental results on this apparatus, we constructed a large scale thermoacoustic Stirling cooler. As shown in Fig. 6, this cooler consisting of t ubes with inside diameter of 10cm is 0.6 m in height, and 4 m in length, respectively. This device could achieve a greater cooling power. This result was reported on newspapers as a new technology to produce low temperatures.

4. NEXT STEPS

Thermoacoustic devices are simple and reliable because of the absence of moving parts. Furthermore, since they use inert gases as a working gas instead of Freon gas, thermoacoustic devices can be environmentally attractive heat engines. The research group in Los Alamos national laboratory is developing a thermoacoustic natural gas liquefier powered by burning natural gas[16]. Recently, we have succeeded in amplifying the work flow by inserting a differentially heated regenerator into a wave guide[5]. This technique might be useful in constructing acoustic networks having many regenerators, which work as a power amplifier and a heat pump. A "dream pipe"[7, 8] significantly enhances thermal conduction from hot to cold using oscillating fluid. This would play more important role in the applications such as a heat radiator than a thermoacoustic cooler. A high power thermoacoustic device for a practical use inevitably involves high amplitude acoustic waves. Suppression of the formation of shock waves [17] and acoustic streaming [12] will be important issues in improving the performance of the practical device. Thermoacoustic phenomena are also interesting from the viewpoint of nonlinear systems [18, 19]. A substantial development has been made in study of thermoacoustic phenomena

over the last two decades by a few groups [20]. There is still much left to be done for the development of practical devices.

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The Crystal-Growth Control-Substance from Organism

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1. ICE-NUCLEATING PROTEINS [1–5]

Generally, water freezes at 0 ºC (at an atmospheric pressure of 1), but it is actually extremely difficult to freeze pure, distilled water droplets, requiring temperatures of around –39 ºC. There must be impurities in water around which ice crystals can form if the water is to freeze without supercooling. One such substance is silver iodide. When pure water freezes, several water molecules cluster together and this becomes the ice nucleus around which the freezing process occurs. Normally, however, water contains impurities and these impurities become the nucleus around which the ice begins to develop. *Pseudomonas syringae* is a bacterium isolated from fallen leaves that promotes freezing. It is one of four genera now known to stimulate ice formation:*Pseudomonas*, *Pantoea (Erwinia*), *Enterobacter,* and *Xanthomonas*. These bacteria produce a substance that allows the freezing of water droplets at higher temperatures than the well-known ice nucleation substance silver iodide. Whereas half of 30 water droplets (equivalent to 10 micro-liters) treated with silver iodide will freeze at –7 ºC(T_{50}), half of the water droplets treated with an ice nucleation bacteria freeze at –2 ºC(T_{50}). The ice nucleation protein in these bacteria has many repeating amino acid chains. This amino acid structure is important because it arranges the water molecules into a pattern that promotes crystallization. It is extremely thought-provoking that bacteria should play a major role in the freezing process, once thought to be purely a physical process. By studying these bacteria, scientists may be able to make use of the phenomenon. The electron photomicrograph of broth-growth cells of the ice-nucleating bacterium KUIN-1 are shown in Fig. 1.

It was recently discovered that under specific culturing conditions the bacteria *Xanthomonas campestris*, which also produces the xantham gum used to increase the viscosity of food products, produces a substance that promotes the freezing of water outside of the organism. Use of this substance would eliminate any hygienic problems, opening the door for possible applications to frozen foods, frozen concentrates (food, enzymes, and pharmaceuticals), frozen pharmaceuticals, coolants, and heating agents, This substance could even be sprinkled on clouds by airplane to avert major snowstorms. Comparison of the ice nucleating bacteria and non-ice-nucleating bacteria are shown in Table 1.

Measurement of the ice-nucleating temperature : The ice-nucleating temperature was measured with a freezing nucleus spectrometer, as described by Vali[4]. Thirty drops, 10 μ*l* each, were placed on a controlled-temperature surface, and the temperature was slowly lowered from ambient to –20 ºC at a rate of 1 ºC per min. The temperature required to freeze 10% (T_{10}), 50% (T_{50}) and 90% (T_{90}) of the drops were used in the analyses.

2. ANTIFREEZE PROTEINS (AFPs) [5–12]

There are many places on the earth where it is hard for organisms to survive the cold. Insects living in these areas produce a type of antifreeze in their bodies called polyhydroxy alcohol. The American red frog (*Rana sylvatica*), which is resistant to freezing, has the enzyme oxidase in its liver which when activated breaks down glycogen into glucose. Also, fish living at the poles produce an antifreeze glycoprotein that prevents water in their blood from freezing.

It is my belief that microorganisms, on the earth since time immemorial, must produce their own antifreeze substances just like polar animals. For the past several years, scientists at the Kansai University have been collecting soil, snow, drift ice, fallen leaves, and

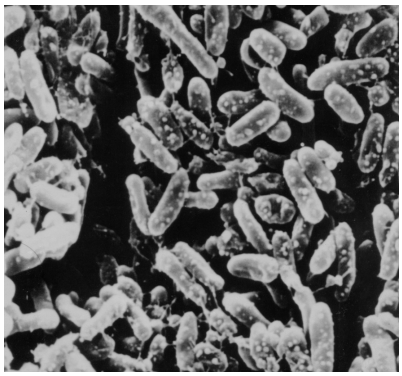


Fig. 1 Electron Photomicrograph of broth-grown cells of the ice-nucleating bacterium KUIN-1.

Table 1 Comparison of ice-nucleating bacteria and non-ice-nucleating bacteria.

Bacterial species [a)]	Ice-nucleating temperature (ºC) [b)]		
	T_{10}	T_{50}	T_{90}
Strain KUIN-1	–2.6	–3.0	–3.1
Pseudomonas syringae (IFO 3310)	–2.1	–2.4	–2.7
Erwinia herbicola (IFO 12686)	–2.9	–3.1	–3.3
Protaminobacter ruber (NR 1)	–8.3	–9.8	–12.3
Corynebacterium sp. (KUP 1)	–13.0	–14.6	–16.0
Staphylococcus aureus (IFO 12732)	–11.2	–15.0	–18.1
Pseudomonas sp. (KUC 7A)	–14.2	–18.4	–20.4
Pseudomonas fluorescens (IFO 3930)	–15.0	–18.4	–19.5
Nocardia globerula (IFO 13509)	–16.9	–18.8	–20.1
Rhodococcus rhodochrous (IFO 3338)	–16.2	–19.0	–20.5
Bacillus subtilis (IFO 3134)	–15.9	–19.4	–20.7
Escherichia coli (JA 221)	–13.8	–20.0	–21.6
Streptococcus faecalis (H21D)	–17.9	–20.7	–22.9
Lactobacillusacidophilus (ATCC 3953)	–18.9	–21.5	–22.5
Distilled water (HPLC)	–18.7	–21.6	–24.1

a) Cells were grown on Trypticase Soy Broth for 24hr at 18 ºC.
b) Temperature required to freeze 10 % (T_{10}), 50% (T_{50}), 90% (T_{90}) of the test samples. (O.D.660 = 0.1)

fresh water lake-fish from cold regions of the world and searching for microorganisms or fish that produce antifreezes.

Recently, we found fresh water lake-fish had AFPs in their body fluids. The results are consistent with previous studies with Antarctic fish. DeVries et al., discovered that Antarctic fish had antifreeze proteins in their body fluids. These proteins are synthesized in the liver and then exported to the serum, where they bind to embryonic ice crystals and effectively impede the further addition of water molecules to the plane of crystal growth. As a consequence, the freezing point of the blood of these fish is lowered to about 1.2 ºC below its melting point.

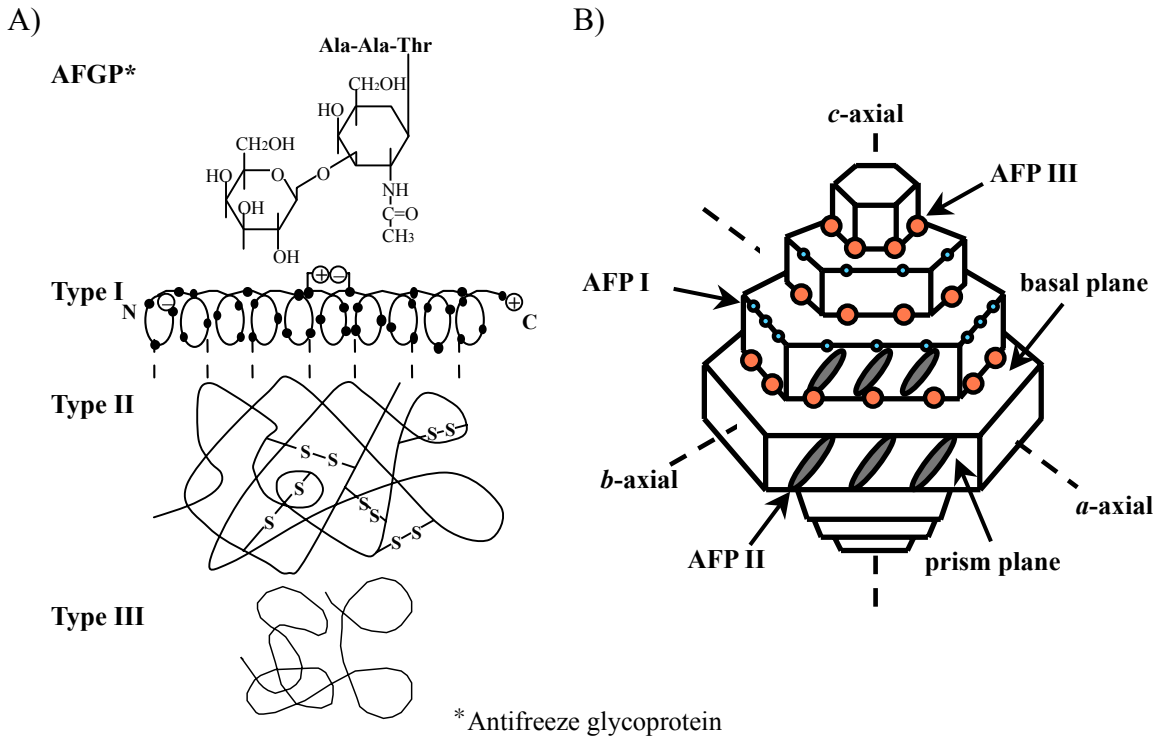
AFPs have the ability to bind to ice crystals and restrict their growth, enabling certain organisms to survive under freezing conditions that would otherwise prove fatal. Although exact details of the antifreeze mechanism have not been established, it is widely regarded that AFPs require some structural complementarity with ice to adsorb to its surface. AFPs have the unique capacity to depress the freezing point of water by a non-colligative mechanism while not affecting the melting point, thus producing a difference between the freezing and melting points which is termed thermal hysteresis.

Some AFPs have been structurally characterized, revealing a remarkably diverse range of protein folds. Of the current five distinct types of AFPs isolated from polar fish, three have solved structures. TypeI AFPs from flounder and sculpin are amphiphilic, single α-helices of ~30 to 50 residues, with putative ice-binding threonime residues repeated every 11 amino acids along the length of the helix. Type II AFPs found in sea raven, smelt, and herring are ~125 residues long and have homology to C-type lectins with a mixed structure containing two α-helices and β-sheets. Type III AFPs, isolated from Arctic and Antarctic eel pouts, are globular proteins of ~65 residues but with a flat ice-binding face. The structures of insect AFPs from the spruce budworm moth and the mealworm beetle have recently been characterized as parallel β-helices in the left- and right-handed orientations, respectively. Schematic representations of the four AF(G)P structures and interaction with ice are shown in Scheme 1.

Thermal hysteresis and shapes of ice crystal: The antifreeze activity of purified sample of protein was assayed by the method of Meyer et al.[13]. The assay is based on changes in the shape of seed ice crystal caused only by AFPs. The temperature was then increased until the ice crystal slowly melted and this time from the start of heating to the start of melting of the ice crystal was measured.

One-sixtieth of the rate of 1 ºC/min (60 sec) times the time (sec) was defined as thermal hysteresis(ºC). Under these conditions, as for AFPs of some other fish, antifreeze activity was taken to be high when the ice crystal was multifaceted or bipyramidal(9), and antifreeze activity was taken to be low when the ice crystal was flat and hexagonal. With no antifreeze activity, ice crystal was spherical disc.

Organisms develop a variety of strategies of survival and in areas with low temperatures they have acquired defensive methods to survive the cold through the process of evolution. Presently, we are investigating the various properties of bacteria antifreeze proteins and looking at the possibility of practical applications. The freezing of foods halts the activities of microorganisms and enzymes, thereby halting metabolic and biological changed by freezing can be preserved in their fresh, raw state.



Scheme 1 Schematic representations of the four AF(G)P structures and interaction with ice.

However, physical changes from freezing can occur depending on freezing and preservation conditions. Examples are ice sublimation, oxidation and break-down on fatty acids, destruction of food tissue from ice crystallization, chemical changes caused by freezing, conversion of alpha starch to beta starch, and changes in the solubility of proteins. We may be able to learn how to minimize these changes by studying the strategies of organisms that can survive in freezing conditions. These organisms do not freeze even when covered with a layer of ice. Perhaps by incorporating an antifreeze within frozen foods, they can be covered with ice without freezing and the problems associated with frozen foods can be reduced. Because of rapid reproduction rates of microorganisms, industrial applications should be simple. Applied research in their use in food preservation and the preservation of transplant organs has begun. Once the safety of using these bacteria is confirmed potential applications will be manifold.

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Some Remarks on the Nukiyama Curve

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It was about 70 years ago when Shiro Nukiyama published his pioneering paper on "Maximum and Minimum Values of Heat Q Transmitted from Metal to Boiling Water under Atmospheric Pressure" [1]. A milestone at the beginning of a long way towards the "truth" in boiling heat transfer. Numerous researchers discovered a lot on this way but the more we find out the more difficult it becomes to really understand this extremely complex process.

Basically Nukiyama's boiling curve has never been disputed. Only specific aspects were and are subject of studies or disagreements. The shape of the boiling curve, for instance, is still a subject of discussions in terms of its behavior in the transition region, its change in a transient situation with respect to the steady-state case, its dependence on contaminations on the heating surface etc. The shape of the boiling curve and its change under different system conditions is, of course, a result of different boiling mechanisms and their change. Since pure empirism can never solve such problems, several physical models for the different boiling modes have been developed. We should trust these models only after experimental verification. Moreover, due to the improvement of our experimental techniques and also of the mathematical tools in recent years, older and relative simple models can now be improved and new ones can be developed.

The present report makes some remarks on the aspects mentioned above. Of course not comprehensive and – subject of excuse – focused mainly on our own work. It is just meant as a small tribute to Nukiyama's pioneering work. Those who need a sort of survey on new developments may look into the "Proceedings of the 5th Int. Boiling Heat Transfer Conf. in Jamaica, May 2003". A selection of the papers presented there will soon be published in the "International Journal of Heat and Fluid Flow".

HYSTERESES ALONG THE NUKIYAMA CURVE

No contradiction exists about a hysteresis in the region of nucleation incipience (see Fig. 1). In contrast, in transition boiling and for steady-state conditions a hysteresis was postulated [2] consisting of a transitional nucleate boiling–and a film boiling–branch, both overlapping with respect to the heat flux. However, if a precise temperature control system [3] is available and with a clean heating surface, boiling curves even for liquids with large contact angles (water) show no hysteresis regardless in which direction they are measured: stepwise from film to nucleate boiling or vice versa. In contrast, if surface contamination is involved, boiling curves are not reproducible. Each test run, even under carefully established steady- state conditions, results in a shift of the curve already at a minimal change of the deposit [3,4].

The boiling curve behavior changes under transient conditions, even on clean surfaces. Recently it was argued that "how the unsteady process influences the hysteresis is not cleared, yet" [5]. Objection! It is, as shown by systematic experiments in [6]. There, measurements with controlled heating and cooling rates were carried out, of course, by taking into account the "coupling problem [5]" between heater and fluid which requires the solution of an inverse heat conduction problem. One typical result is shown in Fig. 2: The steady-state curve was measured with

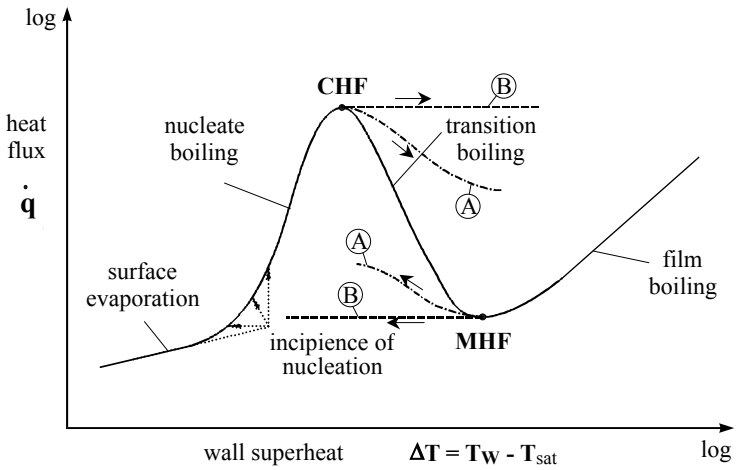


Fig. 1: The Nukiyama curve.

stepwise increasing and decreasing temperature without observing a hysteresis. A transient heating rate of e.g. 4 K/s along the entire boiling curve yields significantly higher heat fluxes at a given instantaneous surface temperature and a transient cooling vice versa. The cooling curve in Fig. 2 results from a quenching process (i.e. no heat input from outside and no temperature control) which yields the fastest cooling of the given heater. Hence, the cooling rate (in K/s) along the curve is not constant. In contrast, increasing the heating rate is less limited by the thermal inertia of the heater. At a nominal heating rate of 50 K/s (not exactly constant along the boiling curve, see [6]) we observed a 4 times larger CHF-value than in the steady-state case. These results from systematic experiments are, however, rather the beginning of the story than the end of it. What is the physical explanation for this enormous hysteresis? Here, first, the experimentalists are needed to look into the two-phase layer near the surface where the governing mechanisms take place and to explore as much phenomena as possible in order to initiate the development of mechanistic models, which are useless without experimental support, at least in boiling.

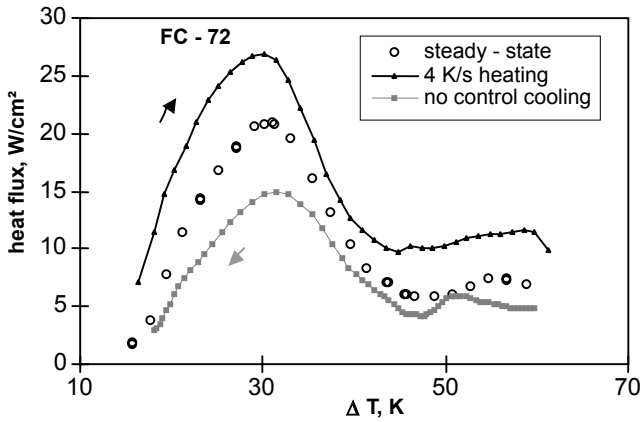


Fig. 2: Boiling curves of FC-72 under steady-state conditions as well as under transient heating and transient

Incidentally, the transient behavior of a boiling curve in an uncontrolled system is often depicted by horizontal lines (B in Fig. 1) for the heating and the cooling mode. Both are physically impossible. Depending on the thermal inertia of the heater the system always moves along lines according to A in Fig. 1. And if somebody call CHF the "burnout point" we should tell him or her that burnout occurs at a much higher temperature if any.

Many experimentalists are fascinated by the challenge to discover the mechanisms of boiling in each regime under steady-state and/or transient conditions in order to explain global experimental findings as those discussed above. For a good survey of recent efforts in this field again the Jamaica-Conference is mentioned. Here only some own findings are picked out.

EXPERIMENTS WITH MICROSENSORS

With thick heaters such as used in practical operation, non-intrusive techniques cannot access the most important parameters on both sides of the heating surface. Therefore miniaturized sensors have been developed which do not significantly disturb the processes.

Micro optical probes (tip diameter ~1.5µm, more details in [3]) reveal e.g. a void fraction (α_v) distribution as shown in Fig. 3 for isopropanol and the fluorinert FC-3284 (3M-company) in fully developed nucleate boiling. Very near to the surface (smallest distance: 8µm for isopropanol; 5µm for FC-3284) α_v is small, but it increases with the distance until a maximum is reached. Hence, a liquid rich layer exists near the surface. Its thickness decreases monotonically with increasing wall superheat and it disappears in high heat flux nucleate boiling [3,7]. The distance of the maximum to the surface is linked with some kind of bubble departure diameter d_B (d_B isopropanol > d_B FC-3284). These findings prove the basic idea of the macrolayer theory but the reality is somewhat more sophisticated, the more so as no stationary vapor stems in the liquid rich zone were observed but always single nucleation sites which are not locally fixed for a longer period. A challenge to improve a popular model for the boiling mechanism!

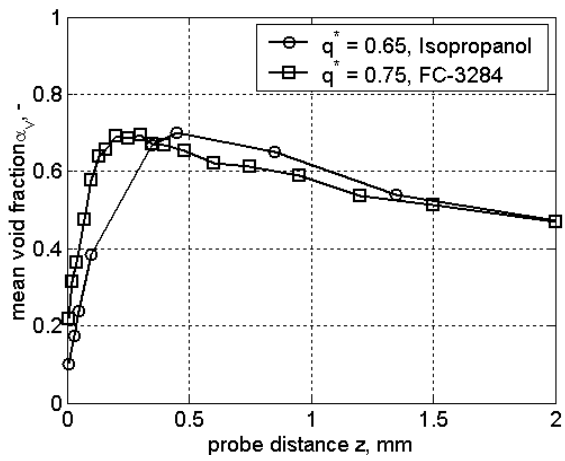


Fig. 3: Mean void fraction for nucleate boiling measured with isopropanol and FC-3284.

$q^* = \dot{q}/\dot{q}_{CHF}$. z: distance to the heater surface.

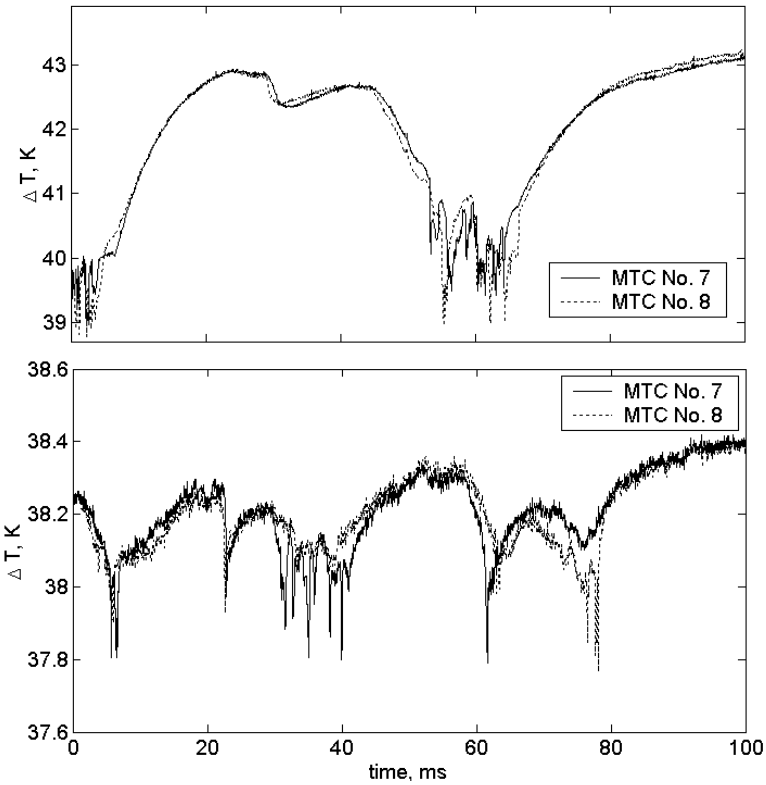
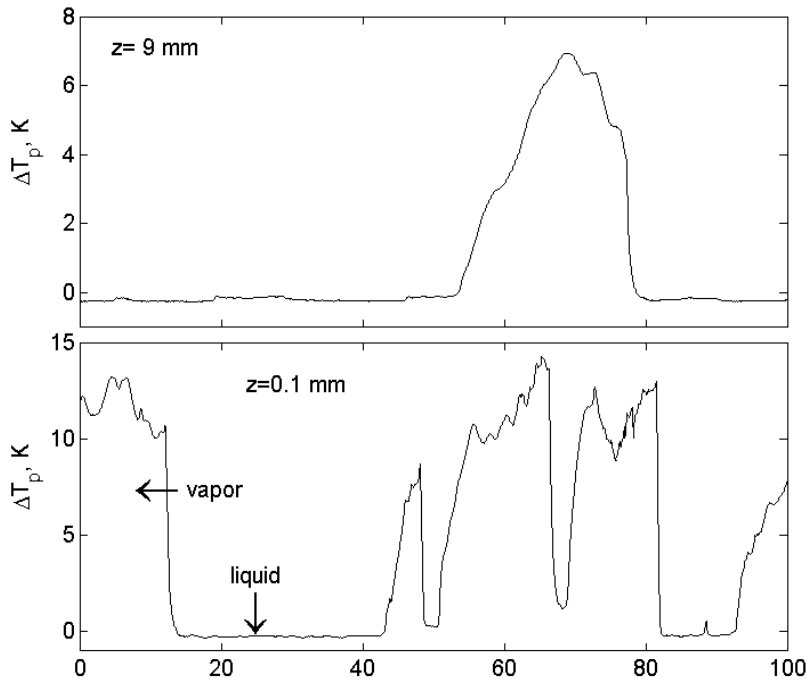


Fig. 4: Temperature beneath the heater surface at microthermocouples No. 7 and 8 in transition boiling; top: isopropanol, bottom: FC-3284. Horizontal distance 7 ⇝ 8: 211.6µm.

Fig. 4 shows temperature traces from microthermocouples (MTC) in transition boiling. The diameter of the MTCs is 38µm. An array of 36 MTCs is implanted in a copper heater within an area of 1 mm² (distance between individual MTCs: about 200µm). The sensitive tips of the MTCs are located 3.6µm beneath the surface (more details in [8]). Measurements of this kind were carried out along the entire boiling curve and several conclusions about boiling mechanisms could be drawn [9]. Just a few remarks: In nucleate boiling several sharp temperature drops have been observed which are mostly not correlated even for MTCs with a distance of only 211.6µm. This is another indication of very localized but strong evaporation near the three phase contact line at the bottom of a bubble. In transition boiling (Fig. 4) dry patches with increasing size towards the Leidenfrost point can be quantitatively identified. In between, fast wetting events occur resulting in a local temperature drop of more than -30,000 K/s for isopropanol. Solving an inverse heat conduction problem, heat fluxes within the wetting zone of up to 8 MW/m² have been identified [10] at wetting events like those shown in Fig. 4, top. In modeling efforts for transition boiling it is often assumed that it consists of a combination of film and nucleate boiling. This is, at least as far as nucleate boiling is concerned, far from reality. The vapor generation process in a wetting zone is much more effective in terms of heat flux than in nucleate boiling. To assume film boiling heat flux in the dry patch area might be more realistic though sometimes droplets seem to wet the surface within a dry zone which we never observed beyond the Leidenfrost point in film boiling.

Let's finally look at Fig. 5. It shows temperature traces of isopropanol in the two-phase layer above the heater measured with a micro thermocouple probe (MTCP) (diameter: about 16µm) in transition boiling. The non-insulated tip of the wire is covered with a 1µm thick gold layer (more details in [9]). This constantan/gold thermocouple exhibits a very short response time. Without going into the details, it is obvious that strong superheats (ΔT_p) are observed in the vapor leaving the surface (z = 0.1mm, $\Delta T_p = T_{probe} - T_{sat}$ ⇝ up to 15K) whereas the surrounding liquid is at saturation temperature. As to be expected, the superheat in the bubbles decreases with increasing distance but at z = 9mm it is still about 7K. Similar measurements in all boiling regimes show an interesting trend: In low heat flux nucleate boiling the bubbles are slightly superheated but surrounded by strongly superheated liquid of several K (for isopropanol) with a sharp temperature drop near the interface. Towards CHF and via transition to film boiling the liquid approaches saturation already in fully developed nucleate boiling whereas the superheating in the bubbles steadily increases (up to more than 30K at z = 0.1mm for isopropanol) in film boiling. Even at larger distances (e.g. z = 9mm) we are far away from thermodynamic equilibrium.



WHAT'S NEXT

Shiro Nukiyama would probably say to the boiling community: Continue to carry out experimental and theoretical studies on the fundamentals. In this way it is still possible to better approach the "truth" in boiling. On the next Conference we will see if his opinion was realistic or not.

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Reviews of International Conference
The 21st International Congress of Refrigeration

A Successful Venture!

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It had been over 30 years since the International Congress of Refrigeration was held in the United States. During that intervening time, the energy crisis loomed, refrigerants began to be phased out, and HVAC&R technology changed significantly. The 21st IIR Congress, held in Washington, DC this past August, gave us an opportunity to work with our colleagues from around the world and share ideas that may shape products for the next thirty years. With 'Serving the Needs of Mankind' as its theme, over 750 people from 58 countries attended this important event.

Each morning's plenary session included a noted speaker. Nobel Laureate William Phillips of NIST opened the Congress, speaking about breakthroughs in low temperature physics while entertaining the crowd with some fascinating demonstrations. USDA Undersecretary Elsa Murano spoke of new federal initiatives in food safety. During these plenary sessions, the audience also heard about the history of refrigerants and how the IIR has served the needs of mankind for almost 100 years. On the final day, David Herbek from NASA spoke about comfort conditioning for the International Space Station.

The attendees also viewed a five-part video called "Serving the Needs of Mankind". This video traces the history of refrigeration and air conditioning. (The congress organizers are currently assessing whether there is widespread interest in making the video available.)

Approximately 440 papers, by 1031 authors from 46 countries, were presented at the Congress. Many of them had to do with new technology; e.g. CO_2 systems, advanced heat exchange techniques,

IIR Director Francois Billiard presenting his plenary speech on the contributions of IIR in serving the needs of mankind

Attendees enjoying a bountiful repast at the Reagan Building reception

Dave Herbek of NASA describing challenges in air conditioning the International Space Station

Congress attendees at one of the many technical sessions

Boarding a bus for a technical tour

absorption systems, and the cold chain. All papers are included on the Congress Proceedings CD ROM, which will be made available for purchase at www.icr2003.org. In addition, thirteen short courses were held ranging from technician certification to handling cryogenic fluids.

In addition to the variety of Washington tours offered to the delegates and those accompanying them, there was also a wide selection of technical tours, including visits to two ARI members' facilities, viewing bio-cryogenics at the National Zoo, and visiting the retrofitted cooling system at the National Cathedral.

Woody Sutton, ARI President presenting remarks at the Congress Banquet

The social highlight of the week was the IIR Awards Banquet. ARI President Woody Sutton addressed the banquet. Several IIR awards were presented, including seven to outstanding young researchers in the refrigeration field. USA researchers captured two of the main awards and two of the young researcher awards.

Many people worked for several years to make the Congress a success. Your support is especially appreciated.

The Congress was an opportunity for American industry to act as hosts to the world, to highlight American technology and to highlight the International Institute of Refrigeration, while learning from our colleagues abroad. From all accounts, these objectives were met with flying colors!

Impression of 21st International Congress of Refrigeration

Prof. Ruzhu Z. Wang

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The five day program of ICR2003 in Washington D.C. (Aug.17-22, 2003) was very busy. The overarching theme of the Congress is *Serving the Needs of Mankind.* The Congress was a celebration of how refrigeration has -- and continues to -- serve the world's need for safe food, efficient industry, widespread medical care, and physical comfort. The IIR Congress is held every four years and is the major forum for the exchange of technical information involving refrigeration. The IIR's mission is to promote knowledge of refrigeration technology and all its applications in order to address today's major issues, including food safety and protection of the environment (reduction of global warming, protection of the ozone layer), and the development of the least developed countries (food, health). The IIR commits itself to improving quality of life and promotes sustainable development. The total participants this time were estimated as 700.

The well researched areas for refrigeration and air conditioning equipments are heat pump, sorption cooling etc.. For example, there are 157 papers related to heat pump, 40 related to absorption, 12 to adsorptiion, 7 to desiccant. There are 22 papers dealing with CO2 refrigerant, 9 papers related to ammonia refrigeration. For the fundamental researches of refrigeration and its applications, there are 150 papers related to heat transfer,35 to thermal physical properties.

BCHP is a warming research area, the research projects of DOE-USA has been paid more attention through short courses and also technical visit. But there are limited researched papers in this issue, this is possibly due to the not enough studies, the researchers have focused more on the system integration, less on their thermal economic studies. The current 10-year payback period is its obstacle to develop such system quickly.

As usual, ICR has include a lot of research papers in the area of food science and preservation, Cryogenics, HVAC systems and IAQ. The last 20th ICR was held in Sydney, there were more than 1500 participants. The 21st ICR in Washington had a small participants possibly due to the politics in USA, and also the SARS influences of this spring. The next 22nd ICR will be held in Beijing in 2007. Anyway ICR has established a good worldwide platform for exchanges of the experiences in refrigeration and HVAC area.

I'm longing for something new

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I participated in the 21st IIR International Congress of Refrigeration (ICR) held in Washington D.C. from August 17th to 22nd in 2003. Although it was first time for me to attend the ICR, I had good time at the conference because I had been at University of Maryland, very close to Washington D.C., for about a year and I met many friends there. An atmosphere of the conference was not so different from that of other conferences related to refrigeration such as Purdue conference or ASHRAE meeting except that there were many short courses and technical tours. And one more thing I felt different was that there were only a few engineers from the Japanese companies because of somewhat academic characteristics of the conference and economical condition of the Japanese companies. Since the congress had ten themes from cryophysics to heating and cooling systems for buildings and maximum eight technical sessions were held in parallel, I can not follow all of the papers and I would like to review some papers in which I was interested.

Needless to say, it is important to improve each component in conventional refrigeration and air conditioning systems. But in order to realize sustainable society, it is also important to do something new. The key words for that, I think, will be integration, thermal storage, heat and loss recoveries and novel concepts of refrigeration principle. Among them, I focus on the third one because I am working on an expander for CO_2 cycle. In addition, I introduce some researches from my personal interest.

An expander or an ejector is studied to recover throttling loss of vapor compression cycle. We presented the performance of a vane type expander which was developed for CO_2 cycle both theoretically and experimentally (Paper No. ICR251). The total efficiency of the prototype expander was 40% and the COP improvement of the cycle was obtained by 20%. H.J. Huff and R. Radermacher (ICR485), University of Maryland, used a scroll compressor as the expander for a larger CO_2 system and almost the same efficiency was achieved. J. Nickl et. al. (ICR571), Technishe Universität Dresden, developed a third generation CO_2 reciprocating expander which has three independent expansion stages. They proposed the cycle with two expansions working in parallel. One expansion process is from supercritical to medium pressure level, while the other is to low pressure level in which two cylinders of the expander are used in series. Besides that, S. Zha et. al. (ICR089), Tianjin University, compared the different types of expanders for CO_2 cycle and examined the performance of a rolling piston expander theoretically. A turbo expander was considered for domestic refrigerator by A. Zoughaib and D. Clodic (ICR 144) of Ecole des Mines de Paris. Although these two were theoretical studies and seem to have little feasibility, it is good that many researchers are interested in the different types of expander and their applications. The ejector is another equipment recovering the throttling loss and many researchers are studying a two-phase ejector recently. Although the efficiency of the ejector is not so high, the extracted work can be directly used as the booster in the systems. In Japan, the ejector is installed to the refrigeration cycle for refrigeration vehicle and CO_2 water heater recently. D. Butrymowicz (ICR310) of Polish Academy of Sciences examined the theoretical performance of the cycle with the two-phase ejector and showed the metastable flow observed in his experiment. Concerning the heat recovery, J.J. Brasz and B.P. Biederman (ICR587), Carrier and United Technologies Research Center, presented low temperature waste heat recovery using refrigeration equipment. They chose R245fa as a working fluid in Organic Rankine cycle. Since power density of the R245fa under the turbine operation matches with that of R134a under the compressor operation, an existing single-stage centrifugal compressor can be used as an expander by redesigning only a transonic pipe diffuser into a supersonic nozzle. The temperature of waste heat in their system ranges from 150 to 400 °C. G.J. Zyhowski of Honeywll (ICR508) also presented R245fa Organic Rankine cycle. Adsorption system can be driven by lower temperature heat sources and many studies were reported in the sessions of B1-23 and B2-17, 18.

Something new is what everyone is looking for at the conference. A. Yokozeki (ICR102), DuPont, correlated the thermodynamic properties of ammonia and n-butane mixture, and the cycle performance with the heterogeneous systems (vapor-liquid-liquid equilibria) was calculated. The cycle using the mixture showed attractive performance, although the flammability and toxicity issues remain and beneficial effects on heat transfer in VLLE flow must be studied. G.F. Nellis et. al. (ICR200) of University of Wisconsin-Madison

evaluated several refrigeration systems including vapor compression cycle, absorption cycle, Stirling cycle, magnetic cycle, thermoelectric cycle, desiccant-assisted evaporative cycle and others for a microclimate cooling by using a thermodynamic system model and a rating system. They concluded that the mechanical refrigeration system or the evaporative cooling systems were attractive depending on the conditions. Although the original purpose of the system is for metabolic heat removal of soldiers and most of Japanese universities can not accept the researches for military applications, this type of study is very important to extend the technology to other fields. The cooling by electrochemical reactions may be feasible concept. D.W. Gerlach and T.A. Newell (ICR338) of University of Illinois at Urbana-Champaign demonstrated the cooling effect by the electrochemical process. Although preliminary modeling results indicate that the peak cooling power occurs at a COP that may be too low for practical use and investigations of potential chemical reactions, cell material selection etc are needed, such attempt is attractive and important for future system.

The necessity of integrated system to save total energy consumption will be getting larger, and the cooperation and exchange of information with researchers in other fields are very important. I am still longing for something new in the refrigeration field, and looking forward to hearing new inventions at the next IIR Congress held in Beijing in 2007. Of course, I hope I make something new.

Cool Guys Gathered in the United States Capital

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After 30 years, International Congress of Refrigeration, ICR, returned to the United States of America. The nation has the largest air-conditioning and refrigeration industry in the world. International Institute of Refrigeration, IIR, headquartered in Paris, is the largest international organization for the people who are involved in air-conditioning and refrigeration. IIR hosts the International Congress every 4 years. On Aug. 17-22, 2003, the 21st International Congress of Refrigeration was held in Washington DC, USA. Every ICR has a theme for the event, and this year's theme was "Serving the Needs of Mankind". There were over 750 participants from more than 50 countries, according to the congress organizer. More than 400 papers were presented, and covered an extensive area of interest.

One interesting point is that the number of participants from Japan was reduced dramatically, compared to several years ago. In contrast, there was a tremendous increase of the participants from South Korea and China. It really seems to reflect the economical growth in these regions.

The high quality plenary sessions started every morning with an amazing short film about the cool history, and was followed by carefully selected key note lectures by well recognized experts in his/her area. The plenary sessions were so successful the conference hall was filled early morning! There were also 13 short courses held during the congress.

The following key themes were covered in papers and posters presented during the congress:

- Refrigerants: new applications for CO_2
- Refrigeration systems: improvement of energy efficiency
- Refrigeration of foods: safety and quality
- Refrigerated transport: new developments
- Air conditioning: performance and health issues
- Heat pumps: equipment and applications
- Cryogenics: systems and components.

As compared to previous congresses, the interests related to refrigerants and their systems have changed from HFCs, the alternatives to CFCs, to natural working fluids, namely carbon dioxide. At least 25 papers were dedicated to CO_2, and covered a wide range of interest, from thermophysical properties to component and system development. The CO_2 system has been under development for about the last 10 years. In spite of its inherent low performance for high ambient temperature applications, CO_2 systems have begun to see some success in certain applications, such as, CO_2 heat pump hot water heater and CO_2 mobile air-conditioning system. The secondary loop system for refrigeration system in supermarket or storage warehouse has received great interest also. For the components, the micro channel aluminum heat exchanger seems to be the most promising choice, and various types of expanding devices are also received tremendous attention. It seems, still many issues have to be addressed to find not only a cost effective way but also an environmentally friendly way to compete with HFCs, non natural working fluids, systems, especially for the air-conditioning applications. Maybe the best solution to solve this dilemma is another governmental regulation.

The CHP, combined cooling, heat and power, and/or heat activated systems became popular, in this congress. Driven by the deregulation and energy saving demands, the distributed power system become a realistic solution, and waste heat driven systems, such as desiccant and absorption systems, are under the spot light once again. More than 26 papers are dedicated to absorption and cogeneration systems. There was even a short course dedicated to the absorption system. The president of Broad, a newly succeeding Chinese manufacturer, appeared to give a presentation of his full product line. Appreciating the Chinese rapid economic growth, the Broad company, comes from nowhere, has become the largest absorption chiller manufacturer in China, today. Its products line covers capacities from several tons to several hundred tons. Considering the miserable absorption chiller market in the US, integration and optimization of the whole cogeneration system seems to be the key issue to achieve success in the market. Moreover, it seems Asian countries are more interested in CHP systems and energy saving technologies than the United States, the largest energy consumer in

the world. The low energy price policy is now becoming a barrier for introducing new technologies into the United States.

The entire congress was very well organized, no surprises, no dark horse. The next one will be in Beijing in 2007. I hope there will be some surprises beside Chinese cuisine and adsorption manufactures. I would like to express my appreciation to Dr. Reinhard Radermacher and Dr. Yunho Hwang of CEEE, University of Maryland, for their valuable comments.

Review on research trends of B1 and B2 sessions

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The 21st International Congress of Refrigeration was held in Washington, DC, USA, August 17-22, 2003. This article introduces Commissions B1 and B2 of International Institute of Refrigeration (IIR) and reviews research trend based on technical papers presented at the B1 and B2 sessions in ICR2003.

The Section B (Head, Professor Watanabe, K., Japan) consists of Commission B1 (President, Professor Bullard, C., USA) and Commission B2 (President, Professor Gorenflo, D., Germany). **The Commission B1** (Thermodynamics & Transfer Process) deals with new fluids and energy efficient transfer processes in advanced refrigeration techniques. In the area of thermodynamics, they concentrate on properties of HFC refrigerants, properties of natural refrigerants, properties of ice slurries. In the area of transfer processes, they concentrate on micro effects, saving of energy, saving of resources and life cycle climate performance. **The Commission B2** (Refrigerating Equipment) deals with new fluids, new systems and systems integration. They concentrate on compressor design and performance analysis, evaporator/condenser and other exchanger design, energy efficiency of refrigerating equipment , absorption/adsorption and ejector systems, indirect cooling systems: liquid secondary and phase-change refrigerants, containment, recovery and destruction of refrigerants, and regulations/standardization/testing

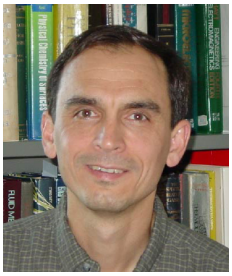
At the B1 session in ICR2003, one keynote paper and 113 technical papers (77 oral and 36 poster presentations) were presented. As a keynote speaker, professor D. Gorenflo (Germany) summarized presentations on new fluids and their energy and mass transfer processes in advanced refrigeration technologies. Thermal/transport properties and heat transfer tests of CO_2, R-134a, 410a, 125, 600, 600a, 401b were presented. Absorption/adsorption fluids for open and closed systems and micro-channel heat transfer were also presented. The highlighted topics were CO_2 heat transfer characteristics and micro-channel heat transfer related to CO_2 refrigeration. Most of participants have interests in CO_2 refrigerant for automobile and residential air-conditioning applications.

At the B2 session in ICR2003, one keynote paper and 86 technical papers (55 oral and 31 poster presentations) were presented. As a keynote speaker, Professor R. Radermacher (USA) made a presentation on integration of air-conditioning and refrigeration with distributed generation. The main topics in B2 session were CO_2 systems, absorption systems and vapor compression systems. The CO_2 systems were also paid attention by many participants from US, European countries including Norway, and Asian countries including Japan, Korea and China. The sorption refrigeration systems were also highlighted to enhance the heat and mass transfer performance by mechanical and chemical treatments. There was a report that the chemical treatment had more significant effect on the absorption performance than the mechanical treatment. Professor F. F. Ziegler (Germany) introduced an interesting thermodynamic concept for comparison of open and closed sorption cooling systems.

During the B1 and B2 commission meetings, Professor H. Auracher (Editor in Chief, International Journal of Refrigeration) presented the statistics on the submitted papers (135 papers in 2002, and expected 180 in 2003), acceptance rate (55% in 2002), nationality of authors (15 papers from Japan, 22 from Korea and 25 from China in 2002), and impact factor (1.00 in 2002). It is impressed that more papers are from Aisa (almost 50%) while less papers are from Europe/America(about 40%). The Editor-in-Chief was very proud of Asian Regional Editor, Professor A. Saito (Japan) for his excellent activity. The impact factor is a measure of the frequency with which the “average article” has been cited in a particular year. The impact factor of 1.00 is ranked 11th out of 102 archival journals in mechanical engineering, and 7th out of 36 archival journals in thermal engineering in the level of Science Citation Index (SCI) journals.

I hope this review help all the members to catch the international research trends in the areas of thermodynamics & transfer process and refrigeration equipment.

Report on the XXI IIR International Congress of Refrigeration



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The XXI IIR International Congress of Refrigeration (ICR2003), hosted by The U.S. National Committee of the International Institute of Refrigeration, was held August 17 through August 22, in Washington DC, after a 32-year absence in the U.S. The official attendance of the Congress totaled more than 750 members representing 58 countries. Nearly 440 papers by 1031 authors from 46 countries were presented. Therefore it was fitting that the theme of the congress was global: "Serving the Needs of Mankind." As outlined below, conference chairs Jerry Groff of Groff and Associates and Mark Menzer of the Air-Conditioning and Refrigeration Institute (ARI) planned and organized a stunning conference.

The Congress held six Plenary Sessions including those given by a Nobel Prize winner in physics, an undersecretary for the U.S. Department of Agriculture, and presidents of refrigeration and air-conditioning companies and organizations. “Exploring the Realm of Ultra Low Temperatures,” by Dr. William Phillips caused many to rethink traditional concepts of low temperature, giving many a different perspective of their own work.

The Congress presented twelve short courses, including “Designing Quiet Transport Refrigeration Equipment,” by Richard Wood, and “Refrigeration and Electronic Cooling,” by Reinhard Radermacher. The short course offerings were a good blend of traditional and novel refrigeration.

Nine tours were given, including one to my Group’s laboratory at the National Institute of Standards and Technology (NIST). We welcomed three groups of bright and curious visitors to our lab where we shared our research on two-phase heat transfer, system simulation modeling, micro electro mechanical systems (MEMS) technology, and with environmental test chambers. Other tours to refrigeration manufacturing plants were also scheduled – including a tour to see the HVAC systems of the gothic Washington Cathedral.

Washington proved to be an excellent host city for the social events organized by the Congress. Tours presented the visitor a revealing view of the U.S. capitol with excursions to the F.D.R. Memorial, Capitol Hill, Georgetown, Embassy Row, and other places of history, charm and power.

In keeping their promise: “providing for the refrigeration needs of mankind,” the Program Committee Chairs Ray Cohen and Eckhard Groll provided a technical program for the interchange of new ideas and latest work in the field using ten timely conference themes: *Cryophysics and Cryoengineering: Keys to Advanced Science and Technology*

Advances in Gas Separation and Cryogenics; New Fluids and Energy Efficient Transfer Processes in Advanced Refrigeration Technology; New fluids, New Systems, and System Integration; Advances in Understanding Mechanisms of Natural and Artificial Freezing and Chilling Injury; Refrigeration for Preserving the Quality and Enhancing the Safety of Foods; Refrigerated Storage for Safe, Good Quality Food; Safety and Quality of Transported Food; Engineering Better Working and Living Environments; and, Energy-Efficient Heating and Cooling Systems for Buildings.

The 21st International Congress of Refrigeration

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The 2003 International Congress of Refrigeration was held in Washington, D.C., USA, August 17-22, 2003. Participating in this congress and visiting Washington D.C. was especially meaningful to me because of my experience of living in the suburbs of this city with my family and studying at the University of Maryland as a visiting scholar about three years ago. Since that time I have thought of Washington D.C. as a second home. I am happy to write about 2003 ICR held in my memorial place. However, due to my youth, I fell heavy and difficulty to write about ICR, which has such a long history and authority. I would hope that this letter will be thought of as a brief "introduction" or "impression" from a relatively young participant of the congress.

The International Congress of Refrigeration (ICR) is held once every four years by the International Institute of Refrigeration (IIR). The IIR has 57 member countries and this congress has become the primary meeting in which to exchange information and the latest research results in all fields associated with refrigeration among participants from industry and universities all over the world. This congress was comprised of three sessions, a Plenary Session, a Short Course and a Technical Session, which continued for six days from 9:00 a.m. to 5:00 p.m. each day. In addition, Technical Tours were carried out in parallel with the afternoon sessions. Because of the interest of participants in the technical tours, in the afternoon, the audiences in the session rooms decreased and I felt there was little active discussion. However, the technical tours are one of the most interesting features of this congress. This made me realize the value of the technical tours to our young participants, and the importance of the opportunity to visit research facilities and enjoy communication between participants from all over the world.

Technical tours were conducted to seven facilities: a government R&D laboratory (NIST), the Total Energy Demonstration Project (University of Maryland), the Application of Cryogenics (National Zoological Park), a thermal storage system (Montogomery County Community College), a Refrigeration Equipment Manufacturing Plant (EVAPCO), a Refrigeration Distribution Warehouse (Merchants Terminal), Gothic Cathedral HVAC Systems (Washington Cathedral), and a screw compressor manufacturing facility (York Refrigeration/Frick).

In particular, the tour to the renowned National Institute of Technology (NIST) was very popular. The actual number of participants exceeded the number of initial applicants. The research facilities to view research on refrigeration technology including micro electro mechanical systems (MEMS), was also of great interest to the participants. Personally, the trip to Washington Cathedral made a deep impression on me and I hope you all will have the opportunity to visit the Washington Cathedral, which is one of the world's rare applications of air conditioning systems in a gothic style cathedral.

The technical presentation sessions saw a total of 450 presentations, both oral presentations and poster sessions, including 30 from Japan. The presentation topics included: cryogenic and gas processing, thermodynamics in equipment and systems, biology and food technology, storage and transport of perishables, air conditioning heat pumps and energy recovery. In the session on Absorption Fluid and Process and Systems, in which I participated, there were 27 contributions, including six papers by Japanese, and Asian and European presenters were prominent in this session.

Recently, it has been said that refrigeration technology has become a mature technology, and I also think so. Therefore, it may be reasonable that I had difficulty finding new areas of interest at this congress. However, the topics addressed by the ICR are related to our most fundamental needs. As such, we must continue to try to advance this technology including science, absolutely. I like to believe that a novel idea and new technology will arise out of from our trying and effort.

I would like to close by saying that, for myself, participation in this congress and meeting with Prof. R. Radermacher and old colleagues were both enjoyable and fruitful. I look forward to the next ICR.

USA Capital
in Washington DC

IIR/IIF Congress 2003 Washington D.C.

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The Summer of 2003 found members of the International Institute of Refrigeration converging on the capitol city of the United States, Washington D.C., for the 21st International Congress of Refrigeration. Held the 17th through the 22nd of August in the Marriott Wardman Park Hotel, the Congress was organized into parallel sessions that allowed attending members the opportunity to follow their professional interests without overlaps of the various Commissions that make up the IIR. Since members hail from all around the world, the congress also provided an opportunity to catch up with old colleagues and the opportunity to meet new ones. The classical and luxurious hotel down the hill from the National Zoo provided the backdrop for presentations of work completed and discussions of work yet to be done, food shared and company enjoyed.

The Congress started with a bang in the plenary presentation by Dr. William Phillips of NIST (National Institute of Standards and Technology). A Nobel Prize winning physicist. Dr. Phillips entertained and enlightened the crowd with demonstrations of cryogenics aided by liquid Nitrogen and magnetic levitation demonstrations. Dr. Phillips' work is far below the typical realms that most of the IIR membership deal with; even scientists working in cryology probably do not approach the pico-Kelvin range that his laser-cooled atoms reach. Nonetheless, he demonstrated that the field of refrigeration and cooling is more than just keeping humans comfortable or keeping food from spoiling on the way to the supermarket. Cooling is a cutting edge area of research, especially in the realms of the super-cold, and the people looking for ways to remove heat are at the edge of science.

Following the plenary sessions held every morning, the conference sessions were broken up into morning sessions with poster sessions following immediately afterwards in the respective areas of interest before lunch and two afternoon sessions after lunch. Five to six sessions were held simultaneously for each of the allotted times. Each twenty minute presentation contained a summary of months, if not years, of application of the scientific method to refrigeration.

The content of this Congress demonstrated a strong swing towards natural refrigerants. Ammonia, Propane, Isobutane all made appearances, but the fluid of interest was clearly the "new old refrigerant" CO2. Papers involving Carbon Dioxide peppered the sessions involving new fluids, but CO2 research is not restricted to its fluid properties. The high pressures involved mean that new components and new systems are being developed, and many presentations demonstrated active research in those areas as well. Compressor technology, microchannel heat exchangers that are well suited to the high pressures, and new ways of analysing and optimising transcritical systems are all being developed by IIR members.

The other dominant theme of the congress was research in the food sector. The question of how to keep food from spoiling has been of interest for mankind since the beginning of time, but the question only gets more in depth as the distances between food production and consumption get larger. Presentations were made for novel methods of ensuring the quality of commercial food that ran the entire scope of the food distribution chain. Among the papers presented were computer thermal models of individual food items that assist in the initial freezing, environmental modification of the packaging areas of food, high-tech computer controls that were integrated into the transport and storage refrigeration systems, computational simulations of the air distribution inside refrigerated cabinets, concern for the requirements on the "air curtains" in supermarket cases, and analyses of complete refrigeration systems for the supermarkets. From the farm to the dinner table, IIR members are working to improve and ensure food quality.

But the conference was not only presentations of research accomplishments. Each morning, different short courses were held to further the education of the IIR membership, with topics ranging from the basics of the refrigeration cycle to safe methods of handling cryogenic fluids. Interspersed throughout the days, technical tours were offered to give people the opportunity to see facilities where refrigeration work was being done. The tour destinations, like the short courses, varied much in content, from a compressor manufacturing plant, to the NIST laboratory. This author took the opportunity to go on the National Cathedral tour, where the chief engineer spoke to us about the design and workings of the air conditioning.

The refrigeration community is changing quickly to keep up with international agreements regulating ozone

depleting chemicals, the frontiers of science and cryogenics, and also the increasing demands of cooling and comfort that people require and expect. The IIR Congress of 2003 was a chance for the researchers and engineers from around the world working on cooling to gather and share; plan and develop strategies for continuing the advancement of science and education.

Meeting Calendar

[2003], [2004], [2005], [2006]

- 2003 -

International Symposium on Micro-Mechanical Engineering - Heat Transfer, Fluid Dynamics, Reliability and Mechatoronics -
1-2 December 2003, Mechanical Engineering Research Laboratory, Hitachi, Ltd., Tsuchiura, JAPAN
3 December 2003, National Institute of Advanced Industrial Science and Technology, Tsukuba, JAPAN

- 2004 -

The First International Symposium on Micro & Nano Technology (ISMNT-1)
14 - 17 March 2004, Honolulu, Hawaii, USA
Submission of Abstract : 31 July 2003

4th European Thermal Science Conference EUROTHERM &Heat Exchange Engineering Exhibition
29 - 31 March 2004, Birmingham, UK

International Symposium on Advances in Computational Heat Transfer
19 - 24 April 2004, Kikenes and Bergen, NORWAY
Submission of Abstract : 1 October 2003

The 11th International Conference on Fluidization: Present and Future for Fluidization Engineering
9 - 13 May 2004, Ischia (Bay of Naples), ITALY

15th International Symposium on Transport Phenomena
9 - 15 May 2004, Bangkok, THAILAND

ICMF-2004, International Conference on Multiphase Flow
31 May - 3 June 2004, Yokohama, JAPAN
Submission of Abstract : 1 September 2003

ITherm 2004: Ninth Intersociety Conference on Thermal and Thermo Mechanical Phenomena in Electronic Systems
1 - 4 June 2004, Las Vegas, Nevada, USA
Submission of Abstract : 15 August 2003

International Conference on Thermal Engineering Theory and Applications
31 May - 4 June 2004, Beirut, LEBANON
Submission of Abstract : 1 September 2003

2004 ASME Summer Annual Meeting
13 - 17 June 2004, TBD, USA

Second International Conference on Fuel Cell Science, Engineering and Technology
14 - 16 June 2004, Rochester, NY, USA
Submission of Abstract : 24 November 2003

Second International Conference on Microchannels and Minichannels
17 - 19 June 2004, Rochester, NY, USA
Submission of Abstract : 1 December 2003

RAD04, Fourth International Symposium on Radiative Transfer
20 - 25 June 2004, Istanbul, TURKEY
Submission of Abstract : 15 December 2003

Second International Symposium on Micro/Nano- scale Energy Conversion and Transport
11 - 17 July 2004, Seoul, S. KOREA
Submission of Abstract : October 2003

Submission of Abstract : 15 December 2003
12 - 15 July 2004, Lisbon, PORTUGAL
Submission of Abstract : 15 December 2003

30th International Symposium on Combustion
25 - 30 July 2004, Chicago, USA
Submission of Abstract : 1 December 2003

The 7th Asian Thermophysical Properties Conference (ATPC2004)
23 - 28 August 2004, Hefei & Huangshan, Anhui, CHINA
Submission of Abstract : 30 November 2003

World Renewable Energy Congress VIII & Expo
28 August - 3 September 2004, Denver, Colorado, USA
Submission of Abstract : 30 November 2003

6th Gustav Lorentzen Natural Working Fluids Conference - Current Applications and Opportunities
29 August - 1 September 2004, Glasgow, UK
Submission of Abstract : 1 February 2003

13th International Heat Pipe Conference
21 - 25 September 2004, Shanghai, CHINA

3rd International Symposium on Two-Phase Flow Modeling and Experimentation
22 - 24 September 2004, Pisa, ITALY
Submission of Abstract : 24 October 2003

6th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operations and Safety
4 - 8 October 2004, Nara, JAPAN
Submission of Abstract : 1 September 2003

3rd International Heat Powered Cycles Conference
11 - 13 October 2004, Larnaca, CYPRUS

Transport Phenomena in Micro and Nanodevices
17 - 21 October 2004, Kona, Hawaii, USA

AIChE 2004 Annual Meeting
7 - 12 November 2004, Austin, Texas, USA

2004 ASME International Mechanical Engineering Congress and Exposition - IMECE
14 - 19 November 2004, Anaheim, CA, USA

International Forum on Heat Transfer (IFHT2004)
24 - 26 November 2004, Kyoto, Japan
Submission of Abstract : 29 February 2004

- 2005 -

The 6th KSME-JSME Thermal and Fluids Engineering Conference
20 - 23 March 2005, Jeju, Korea

ExHFT-6, 6th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics
17 - 21 April 2005, Matsushima, JAPAN

Heat and Mass Transfer in Spray Systems
5 - 10 June 2005, TURKEY (organized by ICMHT)

Wavelet Transform and Its Applications in Transport Phenomena
October 2005, TURKEY (organized by ICMHT)

- 2006 -

Heat and Mass Transfer in Biotechnology
June 2006, TURKEY (organized by ICMHT)

13th International Heat Transfer Conference
13 - 18 August 2006, Sydney, AUSTRALIA

World Renewable Energy Congress (WREC-2006)
26 August - 1 September 2006, Yokohama, JAPAN

Others

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