Cool! A New Principle Promises to Revolutionize the Technology of Air Conditioning and Refrigeration

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Refrigeration, air conditioning, and the cooling of industrial plants, consume a significant part of the total electrical power production, and account for a very considerable investment in machinery and infrastructure in any developed economy. The security and quality of the world's food supply depends on refrigeration to a large extent; and far from being a luxury, the large-scale use of air conditioning is an indispensible precondition for attaining modern levels of productivity and living standards in many parts of the world. Clearly, any major improvement in the technology of refrigerating and cooling systems would have enormous economic benefits.

A sweeping revolution in the technology of refrigeration may in fact now be on the way, thanks to a fundamental discovery in the domain of *nonlinear oscillations***,** accomplished by the Russian physicists Danil and Yakov Doubochinski in the 1960s and 1970s [3,4].

One of the concrete applications of this discovery, which provided the key to the recent breakthrough in refrigeration, is a new method for the *atomization* of liquids, i.e. the transformation of a continuous liquid into a cloud of tiny droplets. By means of a novel apparatus [1] that is technically simple to realize, but quite sophisticated from a theoretical point of view, it is possible to atomize ordinary water into droplets of average diameters less than a tenth of a micrometer – with a total energy consumption orders of magnitude lower than any heretofore known method. In fact, the process of atomization itself absorbs a large amount of heat energy from the environment, causing a drastic drop in temperature already inside the “reaction chamber” of the device ([1]). Ejected from the apparatus in a dynamically evolving water-air mixture, a portion of these submicron droplets evaporates almost instantaneously, “sucking” heat from their surroundings and causing a further, large drop in temperature of the medium.

This effect opens the way to a much simpler and more economical technology for refrigeration, air conditioning and large-scale industrial cooling, in which ordinary water functions as the refrigerant, and in which the need for energy-intensive compressors and/or large heat-exchanging and evaporation surfaces, demanded by various present-day technologies, is eliminated.

The new refrigeration method, whose performance has been certified by the international industrial certification agency VERITAS, the technical center FRAMATOME/AREVA and France’s LAMI-ENPC, is now moving into the pilot-plant

[1] In this device a pulsed flow of air interacts with an advancing water surface, which has been set into vibration at a widely differing frequency. The special, so-called argumental mode of interaction, set up between these two oscillatory processes, results in a cascade of phase changes in the air-water system, transforming the water into a cloud of submicron-sized droplets. Hence the term, “reaction chamber”.

project stage. While some technical issues connected with the scale-up of this technology remain to be settled, the phenomenon itself is so remarkable, and its implications so potentially far-reaching, that they justify a preliminary report to a larger audience.

The following article has two aims. First, to acquaint the reader with a fundamentally new method for the atomization of liquids – producing clouds of droplets of submicron size with a very small expenditure of energy -- and with its revolutionary applications to the technology of cooling and refrigeration. Second, by way of these applications as pedagogical examples, to introduce the reader to a novel technological principle – or we might better say, a new “technological philosophy” – differing radically from prevailing ways of thinking among scientists and engineers today. The new invention gives us a beautifully lucid example of the way in which false “axioms of thinking”, inculcated by years of training in standard textbook physics and engineering, can long block the way to the discovery of what are actually quite simple solutions to problems otherwise addressed by complex and inefficient technologies. The *basic elements* of the new solution have existed for a long time; all that was lacking was a change in the way of *thinking* about them.

For this reason, it would not be sufficient here to simply present the new invention. In order to make its principles and operation understandable, we take the reader through the following steps:

♦ Firstly, we sketch the conventional (compression/expansion) approach to cooling and the reasons for its low efficiency

♦ Second, we develop the idea – often overlooked due to over-emphasis on the "Carnot cycle" in conventional thermodynamics teaching – of organizing the cooling of a system on the basis of its own internal resources, by a phase transformation.

♦ Third, the strategy is formulated, to greatly accelerate the process of evaporative cooling by atomizing water down to submicron-sized droplets. In this context, we review the principles and limitations of conventional atomizer technologies.

♦ Fourth, we describe the new atomization process and contrast its "miraculous" performance to that of conventional atomization methods. The fallacies of "Newtonian thinking" are identified as the chief barrier standing in the way of understanding the principles behind the new process.

♦ Fifth, the interaction between wind and waves on the ocean, and a simple experiment which readers can perform for themselves, are presented as examples of the "non-Newtonian" type of interactions, upon which the new atomization technology is based.

♦ Sixth, we present the Doubochinski pendulum [3-6,9] as a model for the understanding the basic mechanism of the relevant “non-Newtonian” interactions, introducing the novel concepts of “argumental” (phase-modulated) coupling of oscillating systems, amplitude quantization, spatial heterogeneity, multiresonance and the "law of necessary diversity".

♦ Finally, we indicate how these principles and concepts are embodied in the new atomizing process.

Cooling things down: the hard way

In inanimate Nature, at least on this planet, cooling occurs primarily by heat conduction, convection, radiation or/and absorption of energy, and evaporation of water at ambient pressures. For modest temperature differences these processes are usually rather slow, and are strongly limited by the size of the surface areas across which the transport of heat occurs. The panting of a dog typifies how many living organisms use active measures – in this case, the forced circulation of air – to speed up the cooling processes.

Man has long exploited the evaporation of water, often assisted by increased circulation of air, as a means of cooling. Modern examples include, for example, so-called "swamp coolers", where water is evaporated from porous filter pads, and "misting fans", in which water is injected into an air stream in the form of a fine aerosol. Unfortunately, these devices rarely provide more than a few degrees of cooling, and therefore cannot fully replace modern air conditioners.

Another time-honored technological principle for cooling systems is to maximize the surface area per unit volume in the design of evaporators, radiators and heat exchangers. We still use these principles on a large scale, for example, in the cooling towers that accompany nuclear or thermal power plants. The giant size of such towers reflects the limitations of "natural" cooling processes, even as accelerated by the indicated means.

The main historical breakthrough in "artificial" cooling came relatively late, in the course of the 19th century, with the development of refrigeration systems based on alternating expansion and compression of a coolant medium ([2]). Despite countless improvements, today's mass-produced refrigerators and air conditioners are based on the same principle as their forerunners over a century ago. There have been many technical improvements, but no really fundamental ones.

The principle of modern refrigeration is very simple: accelerate the natural rate of evaporation of a liquid – and thereby the rate of cooling – by *reducing the pressure*. Many will remember the common high-school or university lab experiment: Put some water into a sealed jar, and start to pump out the air using a suitable pump. As the pressure in the jar drops, the rate of evaporation of the water goes up. Finally, the water actually begins to "boil"! We touch the jar, instinctively expecting to find it hot. But no! It is *cold* to the touch; the "boiling" process occurs by absorbing heat from the medium within the jar and from its surroundings. "Boiling" cools!

Modern household refrigerators and air conditioners employ a continuous *closed* cycle, using refrigerant substances having lower boiling points and other more suitable thermodynamic properties than water. The refrigerant fluid flows through an "expander" into a zone of lower pressure, where it rapidly evaporates and cools (see Figure 1). After passing through the cooling coils surrounding the volume to be refrigerated, the evaporated refrigerant is *compressed*, causing it to condense again into the liquid phase. The compression and condensation process releases *heat*, which common

[2] The first operating refrigerator based on an evaporation-condensation cycle was built by Jacob Perkins in the 1830s. The patent (1834) describes the evaporation of a **"**volatile fluid for the purpose of producing the cooling and freezing ... and yet at the same time condensing such volatile fluids, and bringing them into operation without waste". Commercial use of refrigerating systems began in the 1850s, and was first used mainly for the production of "artificial ice".

refrigerators remove using a radiator on their back side. After the compression and radiative cooling, the refrigerant passes again through the expander, and the new cycle continues.

Here we have a method for cooling at very much higher rates, and to far lower temperatures, than would be possible by "natural" evaporation. But we pay a price. Cooling per se, which involves removal of thermal energy from the materials inside the refrigerator, ought to be an *endothermic* process -- one liberating free energy, rather than consuming it. But the method of compression/expansion requires a considerable input of power to operate the required pump or compressor. At the end of each cooling cycle, that power consumption, plus the equivalent of the heat removed through cooling, has been converted into *waste heat*, which must be disposed of. Thus, a modern air conditioner, if simply placed in the middle of a room without a conduit for channeling the waste heat from the radiator to the outside, will actually produce a *net heating* of the room, rather than cooling!

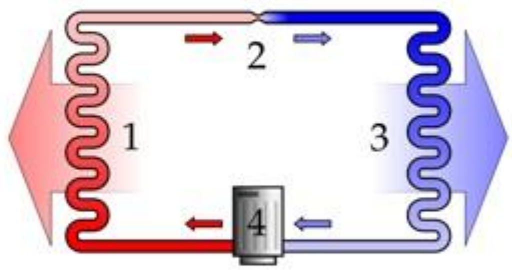

Figure 1
Standard refrigeration cycle:
1) radiator for "waste heat"; 2) expander;
3) cooling coil; 4) compressor.

Back to the Drawing Board

At a superficial first glance, the Second Law of Thermodynamics seems to provide an excuse for this disappointing result. "After all", an obedient student of college physics textbooks might reason: "to cool something down, we must transfer heat from that body to another one. In the case of the refrigerator, from the inside, which should be cooler, to the outside, which is at a higher temperature. But the Second Law says heat never flows by itself from the colder to the hotter, but can only be transferred in that direction by an expenditure of mechanical work. That is exactly what we do in the standard refrigeration cycle. The end effect, of course, in an increase in entropy and a total waste heat which is significantly larger, than the heat removed from the "original body."

Our poor student, stupefied by classroom drilling in entropy and the "Carnot cycle", has completely overlooked the possibility, that a system might cool itself down entirely by its *own resources* – by an internal *phase change*, with little or no external work required! It is exactly here that the originality of the new invention lies: Instead of applying "brute force" to the system from the outside, discover how to exploit the system's own resources to obtain the desired result, via a change in its internal mode of interaction, i.e. its “phase state”. A paradoxical consequence of this approach is that the new method of cooling [1] becomes more and more efficient, as the temperature of the water increases; while standard methods become less effective. The reason is, that the higher temperature liquid has more energy available to organize its own cooling!

In fact, cooling by internal transformation is nothing new, but a commonplace occurrence. It is exactly what occurs, for example, when a certain amount of water or other liquid, placed in a container with a volume of air, evaporates into the gaseous phase, absorbing an amount of heat corresponding to the so-called “heat of condensation” of the liquid. A more impressive illustration of the same principle is provided by the so-called “instant cooling packs” used in medical first aid kits, which use the endothermic reaction of ammonium nitrate dissolving into water, to “suck” heat from the environment. Once the reaction is started, the pack cools down to nearly freezing temperatures, by a purely internal process, with no need for mechanical work and no “waste heat”.

Unfortunately, for many reasons – including the problem of handling and recycling of the necessary materials – the use of such endothermic chemical reactions for cooling is limited to small-scale applications. The evaporation of water**,** on the other hand, presents no problems in supply, handling and recycling. Its main limitation is the relative slowness of the evaporation process under ambient conditions.

With this remark we are back to our original problem: How might we greatly accelerate the “natural” rate of evaporation of water, but this time *without* having to go through work-consuming compression/expansion cycles?

Atomization

A very simple and natural approach is to increase the surface area for evaporation, by first transforming – atomizing – the water into a mist of tiny droplets of smallest possible diameters. The possibility of greatly increasing the total surface area of a given amount of water by atomization is based on the simple geometrical fact, that the surface area of a spherical droplet is proportional to the *square* of the diameter, while the volume goes as the *third power* of the diameter. The ratio of surface area to volume is thus inversely proportional to the diameter, and so increases rapidly as the diameter decreases.

A simple example illustrates the principle. Suppose we could convert a small amount of water, let us say 1 gram (corresponding to a volume of one cubic centimeter), by some atomizing process, into spherical droplets of one-tenth micrometer diameter. The total surface area of the droplets produced from 1g of water, will then be about *60 square meters*! With such a large effective surface area, the original 1 g of water will evaporate extremely rapidly. A moderately warm pool of water with a surface area of 60 square meters, will evaporate about the same amount of water – 1g – or more, *every second* under typical ambient conditions. Assuming that a sufficient flow of air is provided, we can expect a comparable, or even faster rate of evaporation of our atomized 1 gram of water.

The corresponding rate of absorption of heat – i.e. of cooling – is rather considerable. In fact, the evaporation of a single gram of water, removes about 540 calories of thermal energy from the surrounding medium. Assuming a rate of evaporation of 1g of water per second, the resulting rate of heat removal would be 540 calories per second, which corresponds roughly to the cooling power of an average home air conditioner. But to obtain a comparable rate of heat removal by the compression/expansion method, a standard air conditioner needs over 500 watts of electric power. Our atomized mist, by contrast, evaporates spontaneously at the required rate, and does the cooling without any external power input at all. Also, it needs no compressor and produces no "waste heat" that must be removed to the outside. The only byproduct is water vapor. All that must be supplied is one gram per second, or 3.6 liters per hour, of water, and a technical means for atomizing the water down to droplets of submicron size ([3]).

These considerations suggest that evaporation combined with atomization could in principle lead to a very attractive alternative cooling system. Why do we still depend on compression/expansion systems for most of our refrigeration?

Atomization techniques and their limits

In fact, the use of atomized water sprays for evaporative cooling is not new at all. We already mentioned the case of "misting fans", which are widely used in the United States and elsewhere for summer cooling of stadiums and other large open or enclosed areas. The main weakness of these methods, however, and the reason they have not supplanted conventional compression-expansion refrigeration, lies in the very limited effectiveness of existing technologies for the atomization of liquids, particularly where submicron droplets are required. Despite the enormous economic importance of atomizing processes and considerable investments put into research and development in this field, presently existing methods consume *far too much power* compared to the actual rate of evaporation achieved, or have *too low overall productivity*, to make "alternative" atomization-evaporation systems competitive with conventional refrigeration systems in most applications.

The vast majority of industrial atomizing systems produce droplets whose average diameters are on the scale of tens or hundreds of microns – much too large to yield rates of evaporation sufficient for refrigeration purposes. Thus, the so-called "misting coolers" can bring temperatures down by perhaps 10 degrees under favorable conditions, but seldom more.

To produce droplets of submicron dimensions in a reliable fashion by atomization of water, is not an easy task. Existing systems are based either on high-pressure nozzles, or powerful ultrasonic radiators, or some combination of the two. The basic strategy of these devices is to "rip the water apart" by overwhelming force. Some nozzle atomizers produce the droplets directly, by forcing the liquid, under high pressure, through one or more tiny openings. Others, sometimes known as "two fluid" systems, inject water into a high-velocity (sometimes even supersonic) stream of air. They generally require large amounts of pumping power relative to the amount of water atomized, and must be carefully maintained and adjusted to keep the droplet size and flow at specifications.

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[3] Electrical power is also required, of course, to run the device producing the atomization. Indeed, the power consumption of previously-known atomization processes is so high, relative to their yield in terms of submicron-sized droplets, that the indicated method of refrigeration could hardly compete with conventional expansion-compression machines. This situation has now drastically changed, thanks to the extremely low power consumption of the new atomizing device, which is at least two orders of magnitude lower than any other known atomizing process, for the submicron droplet size.

The other main alternative method is to act on the liquid with powerful ultrasonic (high frequency sound) radiation. A common variety of household humidifier device consists of a small ultrasonic generator submerged in a basin of water, with its emitting element – a piezoelectric crystal – pointed upward. When the device is turned on, the water above the emitter appears to "boil" up toward the surface, releasing a fine mist of water droplets. Two main phenomena are exploited in this and other forms of ultrasonic "cold boiling": First, there is *ultrasonic cavitation*: the formation of large numbers of tiny bubbles in the liquid, which alternately expand and implode in tune with the frequency of the signal. Second, the high frequency signal can drive the formation and breakup of tiny waves on the liquid surface, so-called *capillary waves*, At sufficient amplitudes these waves become unstable and expel tiny droplets of water into the air, in a manner somewhat analogous to the spray produced by ocean waves.

Unfortunately, the average size of the droplets produced by commonplace ultrasonic atomizers is typically on the order of tens of micrometers, resulting in rates of evaporation that are far too low to compete with the compression/expansion method of refrigeration. It is possible to reduce the average size of the droplets by increasing the frequency of the ultrasonic radiation and by concentrating it onto a small volume or surface area of liquid. Droplet size is proportional to the inverse of the two-thirds power of the frequency. However, going to higher frequencies – typically in the megahertz range – leads to an enormous increase in the power requirement of the ultrasonic source. There are other complications, too. The performance of ultrasonic atomizers is generally very sensitive to the presence of so-called "cavitation seeds" in the water, and to other parameters that are difficult to control.

In the search for more effective atomizing systems, inventors have had some success in combining the action of ultrasonic vibration with that of nozzles. In one variety of the so-called ultrasonic nozzles, a stream of liquid interacts with shock waves generated in an air stream subjected to a high-intensity ultrasonic radiation field. Using these methods one can produce droplet sizes down into the submicron range, suitable for efficient evaporation cooling, but the power requirements are much too large to yield a real breakthrough.

It is evident that the use of ultrasonic methods is hampered by an inadequate understanding of the physical processes underlying such phenomena as cavitation. Exemplary is the observation that a certain amount of cavitation already occurs at extremely small intensities of ultrasound. The well-known anomalies of "sonoluminescence" also underline the limitations of present theories ([4]).

[4] The term "sonoluminescence" refers to the emission of light from a liquid medium irradiated by ultrasonic radiation. This phenomenon was first discovered, essentially by accident, in 1934. It was immediately recognized that the source of the light was tiny bubbles, generated in the liquid through the process of *ultrasonic cavitation.* An exact investigation of the mechanism of emission of this light first became possible much later, in 1989. At that time, researchers succeeded in producing sustained sonoluminescence in a single bubble, trapped in an acoustical standing wave, and undergoing successive cycles of expansion and collapse synchronously with the period of the ultrasonic signal. It was found that the light was emitted in a succession of short flashes, one for each cycle of the expansion/collapse process. Of sensational interest, and completely unexpected, was the extremely short duration of the individual light flashes – mere tens of picoseconds -- and the predominance of very short-wavelength (ultraviolet) radiation in the spectrum of the light emission. Much evidence indicates that the light flashes are generated at the point of convergence of inward-directed shock waves generated in the implosion phase of the bubble, where temperatures of tens of thousands or (some scientists suggest) perhaps even millions of degrees, are reached. Furthermore, for unknown reasons the addition of small amounts of helium, argon and some other gases to the gas in the bubble dramatically increases the intensity of the radiation. All of these characteristics were unexpected and are still difficult to understand today.

One gets the impression that some new idea, some new principle is waiting to be discovered.

It is here, in the domain of nonlinear oscillations, that a revolutionary breakthrough has occurred, which opens up the possibility of an entirely new approach to atomization and refrigeration.

An impressive demonstration…

At first glance, the apparatus resembles a common paint sprayer: a jar with a cap on top, having a nozzle on one side and on the other side a tube connected to a small, low-pressure air pump. This is the revolutionary atomizing device [1], initially developed in 1995. The heart of the invention is a specially-designed “atomizing reactor”, mounted inside the cap, where a stream of water interacts with pulsating air from the pump.

We fill the jar with *boiling hot water*, screw on the cap, and turn on the air pump. Immediately the reactor emits a fine spray of water mist, forming a cloud which quickly disappears into the surrounding air. We place our hand in front of the nozzle. Amazing! Although the water in the jar remains at near boiling temperature, the spray coming out is *cold* to the touch!

The combination of the atomizing process itself and the subsequent evaporation of a portion of the droplets ejected from the device, has caused a drastic drop in temperature. Within a tiny fraction of a second, the temperature of the water goes from 96 degrees centigrade inside the jar, to below 15 degrees at a certain distance from the spray nozzle.

Even the best atomizers, based on heretofore known principles, do not come near such an intense cooling effect. Moreover, the power consumption of the small air pump – which constitutes the entire external power input of the new device [1] – is only a tiny fraction of the power required by standard atomization systems transforming comparable volumes of water into submicron-sized droplets. Also, the pressures used are extremely small compared to those necessary to operate atomizing nozzles. Measurements, carried out at the research center of the French company ELF in 1996, showed that droplets ejected from the atomizing reactor have diameters in the range of 0.2 micrometers.

The performance of a first, unoptimized prototype of the new cooling system was certified by the industrial certification agency Bureau VERITAS in 2000. More extensive measurements of the device's performance under various conditions, were carried out in 2004-2005 at the Laboratory for Materials Analysis and Identification (LAMI) of France’s École Nationale des Ponts et Chaussees (ENPC). The measurements showed that the specific power requirement of the new device is 10 or more times less than that of conventional refrigeration technology, for the same rate of heat removal! Optimizing the system could reduce the power requirement by an additional factor of two or more, depending on the initial and final temperatures of the water. Furthermore, refrigeration systems based on the new technology promise to be much simpler and cheaper to build and operate, than systems based on the conventional compression/expansion principle. This means a technological revolution.

… and the science behind it

The new method has some rather curious features from a scientific point of view. For example, recent measurements confirm that a large part of the temperature drop – as much as half of it – occurs already *inside* the atomizing reactor, before significant evaporation has taken place! This apparent disappearance of heat "into nowhere" is highly anomalous, if not "impossible" from the standpoint of classical textbook physics! Nevertheless there is no doubt that the anomalous results, described above, are real, including the sudden, large drop in temperature and the extremely small power consumption of the device relative to the quantity of heat removed. The laboratory measurements are unambiguous and conclusive.

Evidently *something very special* is going on in the "atomizing reactor", which requires explanation. Fortunately such an explanation exists, in the form of a fundamental scientific discovery which has been the subject of extensive theoretical and experimental investigations [3-8]. Furthermore, analogies have been found with a number of naturally-occurring processes as well as processes occurring in other technical devices, which make the results of the new approach less surprising. The invention of the atomizing reactor draws upon decades of experience in the development of other applications of the same principle, including a new ultrasonic technology for the production of emulsions [2].

To introduce the essential scientific ideas involved, it is useful to start with a question: If the atomizing reactor is so technically simple and effective, then *why was it not invented long ago*, given many decades of intensive work on atomization of liquids by scientists and engineers all over the world?

The reason, as we shall now explain, is very fundamental and has nothing to do with the details of atomizing or refrigeration per se. What so long prevented this simple solution from being discovered, is the prevalence of certain *deep-seated prejudices and wrong ways of thinking* among physicists and engineers, concerning the *nature of physical interactions* in general. These prevalent habits of thinking, which actually go all the way back to Newton, have long caused scientists and engineers to overlook and unknowingly even *suppress,* in the design of technical devices, exactly the kind of self-organizing nonlinear processes upon which the functioning of the atomizing reactor depends!

The essence of the problem lies in the tendency to think about physics in terms of **forces**, rather than in terms of **interactions.** The Newtonian prejudice regards "forces" – gravitational or electrostatic forces, for example –, as innate, indecomposable entities somehow rigidly attached to the particles of matter. Physical systems are held together and governed by such forces, Newton says. From this is appears to follow, that if you want to change a physical system, you must act *against* those forces, using *opposing forces*. "Force against force!" is the essence of Newtonian physics -- a rather barbaric notion, when one reflects upon it. Is this worthy of the Creator of the Universe?

Approaching the problem of atomizing water from a Newtonian standpoint, the physicist or engineer sees the task as that of "ripping apart" the fluid by overcoming the intermolecular forces holding the liquid together within its volume and on the surface (surface tension). To do that, "violent force" must be applied from the outside: forcing the water at high pressure through holes, churning up chaotic turbulence, bombarding it by intense acoustic radiation, and other forms of torture. Although the idea of exploiting nonlinear effects is not uncommon, scientists and engineers typically tend to think of nonlinearity as something associated with extremely large amplitudes and intense forces, thereby falsely assuming – in accordance with the assumptions of Newtonian mathematical analysis – that processes with small amplitudes can be treated as linear, or approximately so.

Wind and waves – a simple experiment

An instructive example of true nonlinearity is to examine how, in Nature, even mild winds interact with the surface of the ocean to produce waves. This process is rather poorly understood, even today, from the standpoint of textbook mathematical physics, but it is very relevant to the atomization and cooling problem. Indeed, under certain circumstances the interaction of wind and surfaces waves can generate large amounts of spray (droplets) and lead to a drastic increase in the rate of evaporation. In a sense, the new atomizing reactor merely recreates this natural process in a highly intensified and optimized, "resonant" form.

In the wind-wave problem we have no simple array of Newtonian forces, but rather a highly complex, evolving interlinking of two oscillatory processes, each of which "modulates" the other. Key to this process is the fact that real winds in Nature never blow in a constant fashion, but always *pulsate* with a rich spectrum of frequencies. These wind pulsations provoke oscillations on the surface of the water – oscillations having much shorter wave lengths than the air pulses, owing to the much higher density of the water. In turn the water waves modulate the wind, generating additional high-frequency components in the wind's spectrum. In this process, heterogeneous structures emerge, i.e. irregularities in the spatial pattern of the waves, which greatly enhance the efficiency of coupling of the two oscillating processes across a large number of widely differing frequencies. Such coupled oscillatory processes, in which relationships of *phase* play the controlling role, are known technically as *argumental* (or phase-modulated) *oscillations*. Argumental oscillations constitute the central area of basic research, pursued by the inventor of the new cooling process since the 1960s [9, 10]..

The following simple experiment, which any reader can carry out, gives us a model for the kind of process we just described.

The experiment is to apply continuous and pulsating currents of air, channeled through a narrow tube, onto a droplet of water. For this purpose it is convenient to use a large syringe filled with water and oriented with its tip upward, in such a way that slight pressure on the syringe causes a droplet to form at the tip. Now observe and compare the results of interaction between the droplet and a flow of air, directed onto the droplet from above or at some angle, under the following two conditions:

1) when the air flow is constant – when it is generated, for example, by blowing air through the tube at a constant rate;
2) when the air flow is rapidly pulsating – as for example when the tube is connected to a small air pump (membrane pump) of the sort used to aerate aquariums, and which pulsates at approximately 50 Hz.

In the first case (provided the flow is not too rapid) the pressure of the moving air merely deforms the surface of the droplet. Its surface remains smooth, no waves are excited. This case corresponds more or less to the mental image of a “Newtonian force.”

In the second case, the interaction is incomparably more intense, even with a weaker overall air flow. The droplet is violently agitated, with various regions of the surface shooting out like “spikes”, others in “sheets”, depending on the orientation and strength of the pulsating air current.

Note that the length-scale of these *heterogeneous structures* is *much smaller* than that of simple surface waves at the fundamental frequency of the pulsation (about 50mm). This reflects the emergence of higher-frequency components. At a certain threshold strength of the air flow, the droplet suddenly shatters into fragments! Here we have a first hint of the kind of process that occurs in the atomizing reactor [1], but in a vastly intensified, optimized form.

In addition to experimenting with droplets of various sizes, it is interesting also to examine the interaction of pulsating air flows with the surface of water filling a narrow (< 1 cm) plastic cap, whose cross-section is either circular or square. In this case we can examine the pattern of heterogeneous structures more easily, and see how the pattern adjusts itself to changes in strength, angle and positioning of the air flow. We can also observe the relative stability of those structures, as well as sudden “jumps” from one quasi-stable configuration to another – phenomena that are typical of argumental oscillations [3,4], as we shall see in a moment.

It is important to emphasize that the heterogeneous structures, generated by the pulsated air-surface interaction, behave completely differently from the so-called Faraday waves or capillary waves that arise when we place the water-filled cap on a vibrating surface (for example, the cover of the air pump) of the same frequency. The latter represent a relatively linear phenomenon which should not be confused with argumental interactions.

The argumental pendulum

Our experiment and the analogy with the wind-wave interaction, already point in the general direction of the new atomization method [1].. But the actual realization of a device capable of producing submicron droplets with a very small expenditure of energy, depended on decades of experimental and theoretical work on argumental interactions. Much of that work was carried out with the help of simplified model systems, of which the simplest and most important is the so-called *argumental pendulum* – also known as “Doubochinski’s pendulum” – invented by Danil Doubochinski and his brother Yakov in 1968. A brief summary on the pendulum helps elucidate the principle underlying the new atomizing technology. For more details, the reader can consult an article [3].

In its simplest form the argumental pendulum is formed from two interacting oscillatory systems (see Figure 2): (1) a pendulum arm with a natural period on the order of 1 – 2 seconds (corresponding to a frequency of 0,5 - 1 Hz), with a small permanent magnet fixed at its end; (2) a stationary electromagnet (solenoid) positioned at the lowest (i.e. equilibrium) point of the pendulum’s trajectory and supplied with alternating current whose frequency can range from tens to thousands of hertz.

The pendulum arm and solenoid are configured in such a way that the pendulum arm interacts with the oscillating magnetic field of the solenoid only over a limited portion of its trajectory – the so-called "zone of interaction" – outside of which the strength of the interaction drops off rapidly to zero. Within this interaction zone, the electromagnet causes the pendulum to experience a series of alternately accelerating and decelerating impulses, which are interrupted at the moment the pendulum leaves the zone. In case the time, taken by the pendulum to traverse the interaction zone, corresponds to an integral number of cycles of the electromagnet, the effects of the accelerating and decelerating half-cycles will cancel out, and the net effect will be zero. But if the pendulum leaves the zone of interaction after a *non-integral* number of cycles, relative to the moment of entry into the zone, then a net transfer of energy will occur, and the pendulum will experience an overall non-zero accelerating or decelerating effect from its interaction with the alternating field.

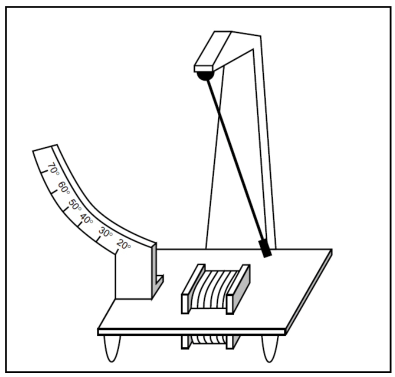

Figure 2
The argumental pendulum of Doubochinski

The key feature of this system lies in the circumstance, that the exchange of energy between the pendulum and the alternating magnetic field, depends on the *phase relationship* between the two oscillating processes, and in particular on the phases of the field at the moment the pendulum enters and exits the zone of interaction.

By shifting those phases the pendulum is able in a sense to *self-regulate* its interaction with the electromagnet. This leads to the extraordinary phenomenon of "quantization" in the behavior of the argumental pendulum, which attracted much attention among leading physicists in the Soviet Union in the 1960s and 1970s, including the famous Peter Kapitza ([5]). Released from any given position, the pendulum's motion evolves, through a sometimes complicated series of intermediate states, into a stable, very nearly periodic motion whose amplitude takes one of a *finite, discrete array of possible values*. In any given such mode the pendulum constantly adjusts its phase relationships with the high-

[5] P. L. Kapitza (1894-1984) was one of the most famous and influential scientists in the Soviet Union. He was awarded the Nobel Prize in physics in 1978. The regular All-Moscow Physical Seminar, held at Kapitza's Institute for Physical Problems, was for decades an important event in the scientific life of the country. The presentation of the argumental pendulum by Danil Doubochinski at the seminar in 1974 caused a sensation among Soviet physicists at the time. Kapitza himself kept a working model of the argumental pendulum, and often demonstrated it to visiting scientists from all over the world. The pendulum can be found today in the museum of Kapitza's institute.

frequency field, extracting just enough energy to compensate its frictional losses over a given period of oscillation.

In a manner reminiscent of the photoelectric effect and other quantum phenomena of microphysics, the number of "available" stable modes of oscillation of the pendulum increases with the *frequency* of the alternating magnetic field, but is relatively independent of its *intensity*. The “quantized” modes are remarkably stable relative to external disturbances. The frequency of the pendulum remains close to its natural (undisturbed) frequency.

This phenomenon of *amplitude quantization*, demonstrated by the argumental pendulum, differs strikingly from the textbook cases of free and externally forced motion of an oscillator and is *completely unexpected* from the standpoint of classical mechanics. In this sense it is justified to speak of a *new physical principle*, manifested in the argumental pendulum’s behavior.

In fact, the relationship of this phenomenon to existing physical theories is rather subtle. On the one hand, there exists a well-developed theory of argumental interactions, and an arsenal of mathematical methods, which make it possible to understand many details of the behavior of argumental oscillators and to calculate the quantized amplitudes in various circumstances. That theory does not appear to contradict the basic "laws" of mechanics as far as they go. But on the other hand, there is no classical explanation for the curious "intelligence" displayed by the argumental pendulum in organizing its transition into a quantized mode and maintaining itself in that mode by means of a complex, quasi-periodic process which might be called of "phase wandering" ([6]).

The authors are convinced that this behavior of the argumental pendulum actually expresses a universal characteristic of matter, lying on the borderline between the living and the non-living. Gottfried Leibniz would have found nothing strange here ([7]). But we must reserve further discussion on this point for another occasion.

[6] The term, "phase wandering”, refers to an important peculiarity in the behavior of the argumental pendulum and similar systems: The motion of the pendulum in its “stationary”, quantized modes is *never strictly periodic*. Instead, the pendulum’s space-time trajectory “wanders” slightly from one cycle to the next, slightly shifting its phase relative to that of the magnetic field and varying its amplitude within a small interval around one of the quantized values. These slight variations allow the oscillator to "feel" its relationship with the external field, thereby maintaining the stability of any given mode. Naturally, the term "feeling" implies an analogy between nonliving systems of the argumental type, and behavior otherwise typical of living processes. To what extent such an analogy is justified in principle, we leave to future discussion. (See also the following footnote.)

[7] Leibniz rejected the notion of Newton, Descartes and others, that matter could exist separately from action. Instead, he held that all phenomena of the physical Universe -- including the behavior of apparently “dead”, inert material bodies – derive from the action of individual substances or active principles, whose nature is most clearly manifested in living processes. In other words, inert matter exists in the Universe only as an appearance or secondary effect (or as Leibniz put it, “a well-organized phenomenon”) associated with the Universe’s ongoing development as a dynamic, essentially “living” process. The entire Universe, Leibniz said, is filled with the incessant activity of living principles or “monads” at every length scale.

Leibniz further emphasized that the empirical laws of motion obeyed by material bodies, such as those which are dealt with in classical mechanics today, cannot be regarded as truly fundamental. Rather, they derive from higher principles governing processes of development. Leibniz’s dynamic, rather than mechanical view of the Universe, is reflected is his choice of the term “vis viva” (= “living force”), instead of what is today unfortunately called “kinetic energy” or energy of motion.

The following analogy, from the domain of optics, may be helpful to some readers in grasping Leibniz’s point: Many optical phenomena can be accounted for in terms of the concept of straight-line propagation of light rays as the supposedly elementary form of light. This is the approach of so-called geometrical optics. We know, however, that in

The role of spatial inhomogeneity

Research on argumental interactions has shown that the "quantized" behavior of the argumental pendulum is shared by a large class of macroscopic oscillating systems. The crucial precondition and common feature is that of *spatial heterogeneity.* This signifies, in technical terms, that the strength and sign of the momentary interaction between the oscillating components of the system, is a function both of the *time* and also of the relative *positions* of those components.

In the case of the argumental pendulum, the spatial inhomogeneity is located at the boundaries of the interaction zone with the electromagnet.

As we pointed out above in the case of the pendulum, the existence of spatial inhomogeniety permits the components of the system to modulate their exchanges of energy via changes in relative *phase*. Hence the expression, "argumental interactions" ([8]).

At the same time, spatial inhomogeneities provide the means for a system to generate an extremely rich spectrum of additional frequency components, that are not present among the proper frequencies (eigenfrequencies) of the individual elements of the system, and which extends far beyond their frequency range.

This is an extremely important feature of argumental interactions, and is key to the functioning of the atomizing reactor [1]. The mechanism of generation of the additional frequency components can most easily be grasped from the example of the argumental pendulum. Although the frequency of the swinging pendulum arm itself is *low* (0,5-1 Hz), its motion across the boundary into or out of the interaction zone causes *very rapid changes* in the accelerating impulse it experiences, depending upon the phase of the magnetic field in the zone at that moment. In this way, the pendulum transforms the *spatial* inhomogeneity into a *temporal* signal with *high-frequency components*.

A simple application of Fourier analysis shows, in fact, that the combination or "interference" between the regular, high-frequency variation of the magnetic field *in time,* and the rapid modulation of that field caused by the pendulum's motion across the inhomogeniety *in space,* produces a rich spectrum of frequency components of the form $F \pm nf$, where F is the frequency of the external field, f is the frequency of the oscillator

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reality a “light ray” is a complex undulatory process, occurring at unbelievably high frequencies; that the appearance of simple, smooth straight-line propagation of light is a kind of illusion, produced only under certain conditions. By altering the experimental conditions in a suitable manner, one can bring forth effects that are totally anomalous relative to the assumptions of ray optics, and which reflect the underlying, dynamic organization of light.

Similarly, the argumental pendulum reveals an unexpected potentiality of so-called “mechanical” systems – a strikingly un-mechanical, even seemingly “intelligent” behavior, reminding us in some ways of living processes. Is this a miracle? Not at all, Leibniz would reply; in the real Universe even apparently “mechanistic” behavior occurs only as a byproduct of processes and principles that are fundamentally non-mechanistic in nature.

[8] In complex analysis the term “argument” denotes the angle defined by a complex number relative to the positive real axis. By its very nature, *angle* signifies *a phase of a rotational process*. The discovery of argumental interactions, underlines once more the *primacy of complex numbers* in physics, as clearly understood by Carl Friedrich Gauss two centuries ago. The concept of *phase* is inherent in all forms of physical interaction in our Universe.

and n is an arbitrary integer, positive, negative integer or zero ([9]). The strengths of those harmonic frequencies depend on the exact form of the spatial heterogeneity, but are generally expressed in terms of Bessel's functions ([10]).

Multiresonance and "The Law of Necessary Diversity"

In addition to the amplitude quantization phenomenon, the argumental pendulum demonstrates the existence of a *mechanism for the efficient transfer of energy between oscillatory processes having widely differing frequencies*, which is entirely unexpected from the standpoint of classical mechanics. This has far-reaching implications, which have been explored and developed in a number of publications [4-7]. The most important points can be summarized as follows:

1. In classical mechanics, efficient transfer of energy – as for example in the case of the action of a periodic external force on an oscillating system – occurs only when the frequency of external force is equal to, or close to, one of the natural frequencies (eigenfrequencies) of the undisturbed system itself. Thus, a pendulum with a natural period of 1 second, will respond significantly only to an external force whose frequency is approximately 1 Hz. This is the textbook case of resonance. But in the case of the argumental pendulum, stable oscillations are maintained through the influence of an external force whose frequency can be 100 - 1000 or more times higher.

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[9] These frequency components arise in the following way. In the simplest sort of argumental oscillator, the "external force" experienced by the oscillating body has the form of a periodic signal Asin(Ft) of angular frequency F, where the amplitude A = A(X) depends upon the body's momentary position as represented by the parameter X. For the case of the argumental pendulum, for example, the amplitude factor A(X) is zero outside the zone of interaction, and has a constant non-zero value inside the zone. Assuming that the position of the oscillating body is a periodic (or very nearly periodic) function of time, with angular frequency f, the function A(X) will also be periodic with the same frequency, and can therefore be expressed as a sum of frequency components of frequencies 0, f, 2f, 3f, 4f, … nf, …. where n is any whole number. Now, it well known that the product of two simple periodic signals of arbitrary frequencies is a sum of components whose frequencies are the sums and differences of the two given frequencies. (For example, sinPt sinQt = ½ [cos(P-Q)t – cos(P+Q)t]). Applying this to the signal A(X)sin (Ft), experienced by the oscillating body in the course of its periodic motion, we see that this signal will be composed of components with frequencies F, F+f, F- f, F+2f, F-2f, F+3f , F-3f … etc.

[10] The mathematically simplest case is when the spatial dependence of the external force has the form of a simple periodic function of the spatial coordinate: A(X) = Asin(kX). This corresponds to the situation of an oscillator interacting with a standing wave. Assuming a simply periodic motion of the oscillating body, i.e. X = a sin ft, A(X) has the form Asin[ka sin(ft)]. The corresponding frequency components can be explicitly determined using the series expansion:

$$\sin[p \sin(y)] = \Sigma_n J_n(p) \sin(ny)$$

in which J_n denotes Bessel's function of order n (the summation being taken over all integers, positive, negative and zero). From this we can easily calculate the harmonic components of the "external force" as modulated by the periodic motion fo the oscillating body, as follows:

$$A(X) \sin Ft = a\sin[ka \sin(ft)] \sin(Ft) = a \Sigma_n J_n(ka) \sin(nft) \sin(Ft) =$$

$$= a \Sigma_n J_n (ka)\ ½ [\cos(F-nf)t – \cos(F+nf)t]$$

Thus, the Bessel functions determine how the strengths of the frequency components of the "external force"-- represented by the coefficients $J_n(ka)$ -- depend upon the amplitude "a" of the oscillator's motion. This relationship plays a key role, in turn, in determining the existence and the specific amplitude values of the "quantized" states of motion of the oscillator. The latter states correspond to the amplitudes (and corresponding phase relationships) at which the oscillating body, oscillating in an approximately sinusoidal fashion with amplitude a and frequency f, resonates with one of the frequency components of the "external source", which were generated by that same motion. For more details, we refer the reader to the bibliography.

As we explained above, the necessary transfer of energy from the high-frequency electromagnet to the pendulum is made possible by the presence of additional frequency components, created by the pendulum's motion in the spatially inhomogenous field of the electromagnet.

2. The basic mechanism of the argumental pendulum can be generalized in a straightforward way to a large class of coupled oscillating systems, which are able to exchange energy via frequency components generated by self-modulation of their interactions.

3. The exchange of energy can go either from the higher to the lower, or the lower to the higher frequency. In the original version of the argumental pendulum, for example, a high-frequency oscillation -- the alternating field of the electromagnet -- "feeds" a low-frequency oscillation of the pendulum arm at a frequency close to the pendulum's own natural (proper) frequency. But not hard to see that the same principle could also operate in the *opposite* direction as a generator rather than a motor – converting energy from the low-frequency motion of a pendulum, via induction, into high-frequency pulses of electrical current.

4. A single high-frequency source can "feed" not just one, but a *large number of different argumental oscillators at the same time*, each operating near its own proper frequency and in any one of its quantized modes. This has been demonstrated in an impressive experiment, in which a single alternating magnetic field is used to drive several pendulum arms of different lengths and periods and several rotors turning at widely differing speeds. All of these systems are seen to operate simultaneously, each of them extracting the energy it needs to maintain its stable motion by means of argumental interaction with the common alternating magnetic field.

5. This demonstration provides a preliminary model for the notion of *multiresonance*: the simultaneous coupling of ensembles of oscillating systems, in a self-regulating manner, across an extremely wide range of frequencies. We believe that multiresonance is crucial to the extraordinary efficiency of self-organized physical processes in Nature. In fact, Nature practically *never* operates on the model of simple, single-frequency resonance, of the sort that still dominates the treatment of resonance phenomena in physics and engineering textbooks today.

6. Nothing exemplifies the multiresonance principle of Nature so clearly, as the manner in which the Earth's entire biosphere is driven by the radiation of the Sun. Multiresonance also pervades the organization of individual cells and living organisms, although this has until now hardly been touched upon by biophysicists. At larger length-scales we have the grand example of our solar system with its array of planets and moons, which preliminary studies [8] have revealed to be another typical example of multiresonant argumental interactions.

7. The case of the biosphere, living organisms and the solar system exemplify still another principle, called "The Law of Necessary Diversity". Put very briefly, it says that the greatest stability and efficiency of a system formed by a population of interacting oscillating systems, drawing their energy from a single high-frequency source, is attained only in a multiresonant mode in which a *maximum diversity of different frequencies and phases* is realized.

Multiresonant atomization

With the preceding discussion of argumental interactions in mind, we now return to the atomizing reactor [1].

Figure 3 shows the reactor in schematic form. A pulsating flow of water enters through a tube at the left, and interacts with a pulsating flow of air, arriving from the air pump through a second tube. Of crucial importance is to insure that the air and water pulsate at widely differing frequencies.

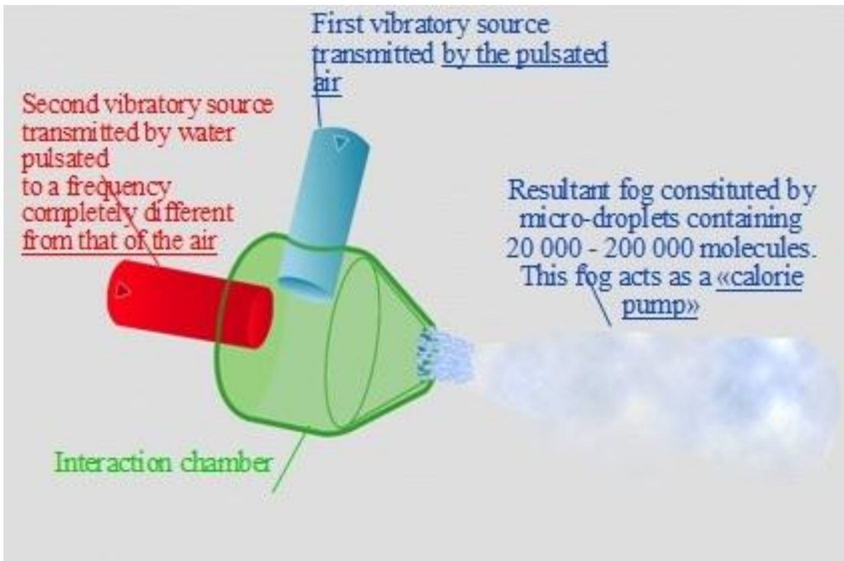

Figure 3
The atomizing reactor

In the prototype version of the atomizing reactor, a air pump provides an initial pulsating air flow at 50 Hz. By choosing the pump and the characteristics of the channel connecting the pump with the reactor in a suitable way, the pulses can be sharpened to have the form of "delta functions": the air arrives into the reactor in short "puffs", 50 times per second. There are a number of different ways to induce the required pulsation of the water for interaction with the air flow. The prototype device exploits certain hydrodynamic processes taking place in the tube and outlet delivering the water into the reactor. This "preparation" insures that the water is already in a heterogeneous vibrational motion at the point it encounters the pulsating air flow.

The atomization process begins at that point, through argumental interactions between the air and water. We could describe the process as "*multiresonant atomization*". It is crucial to stress once more, however, that the type of resonance, occurring here, differs *qualitatively* from the linear sort of resonant phenomena which physicists and engineers commonly employ as their models and mental images for the interaction of oscillating systems.

"Classical" resonance demands close agreement between the frequency of the exciting force and the frequency of some oscillatory mode of the resonating system. In the typical case the engineer must know the precise frequencies at which resonance is supposed to occur (or, in some cases, is to be avoided), in order to calculate the system's design parameters.

The situation is quite different for argumental multiresonance. Here, frequencies do not have to match exactly in order for the oscillating subsystems to interact strongly. The frequencies can be even orders of magnitude apart! Also, the subsystems are able to "intelligently" adjust their frequencies and phases to a considerable extent. Thus, in the case of argumental interactions the engineer can achieve resonant conditions without having to know the precise frequencies of the subsystems.

These considerations are decisive to solving the task of atomization. Not only do we not know the exact resonant frequencies of the components of the water-air mixture at a given moment, but those frequencies are *constantly changing*!

The first challenge for the inventor in designing the system, was to chose and arrange everything, including the parameters of the atomization reactor itself, in such a way as to create the most favorable possible conditions for multiresonant argumental interactions to occur. Second, and related to the first task, is to provide an energetic environment with the richest possible spectrum of excitation frequencies, to "feed" a growing number of oscillating subsystems. Both tasks called for very considerable expertise and experience.

At first glance we might be tempted to regard the pulsating air and the pulsating water, coming together in the atomizing reactor, as analogous to the pendulum arm and electromagnet in the argumental pendulum. The similarity lies in the presence of two differing frequencies, and the spatial heterogeneity insuring the strongly argumental character of the ensuing interaction. However, the water and the air are not simple oscillators! On the contrary, each is a complex system constituted from a huge number of interacting oscillators whose mutual couplings we can act upon via the principle of argumental multiresonance, in order to produce atomization and evaporation.

At the relatively smallest scale we have the molecules of water themselves, which are bound to each other in liquid water by interactions (such as so-called Van der Waals forces) that are ultimately of an electromagnetic and oscillatory nature. Our task is to exploit the internal resources of the system, via multiresonant processes, to reorganize the interactions in such a way that water molecules return to their free, unbound vibrational modes. This is just a different way to say: vaporize the water.

The atomizing reactor achieves this not in a single step, but through a *cascade-like process*, progressively dividing up the water into droplets of decreasing sizes. At any given stage each droplet constitutes an oscillating system within which smaller droplets are already present in a virtual way, as coupled subsystems. We just need to give them a way to tap the oscillatory frequencies they need, via argumental interactions with their pulsating environment, to free themselves from their "bound state" within the larger droplet. At that point, the larger droplet spontaneously disintegrates, with no Newtonian "brute force" required!

The type of multiresonance needed here is of a much more *dynamic* sort, than the above-mentioned example of multiple pendula fed by a single, fixed-frequency signal. It proceeds in the following general way:

The initial "explosion" of the surface of the water flowing into the reactor, as a result of interaction with the pulsed air flow, liberates a cloud of droplets of different sizes, each in a highly agitated, pulsating state. The density of spatial heterogeneities is greatly increased. The smaller droplets, whose diameters adapt to the spectrum of vibrations of the air, have much higher resonant frequencies than the original water surface. The spectrum of water vibrations is enriched and greatly intensified toward the higher-frequency range. At the same time, new high-frequency spectral components are generated in the air, as a result of interaction with the pulsating water droplets and the shock-wave-like signals provoked by droplet "explosions". There are intense interactions between packets of air and droplets of various sizes. Multiresonance causes the droplets to absorb more energy from the pulsed air environment, provoking further ruptures and explosions which produce droplets of even smaller diameters.

With the increasing density of heterogeneities, the increasing surface-area of the droplets and the growing intensity of high-frequency components in the pulsation spectra, the exchanges between the droplets and the thermal medium become ever more efficient. With the decrease in diameter of the droplets, the surface tension is greatly weakened and the droplets become increasingly unstable. The cascade accelerates until the original mass of water has disintegrated into droplets of submicron size. The first half of the job has been accomplished!

Up to the point of exit from the atomizing reactor, the amount of evaporation has remained extremely small. Emerging from the reactor is an extremely heterogeneous mixture of air, some water vapor, and submicron droplets of a large spectrum of sizes, ranging from 200 000 molecules to only 20 000 molecules. Due to their instability, the smallest droplets evaporate nearly instantly, cooling the entire mixture by as much as 40 degrees within a small fraction of a second. This completes the second half of the job!

At the end of the process, what comes out of the atomizing reactor is a mixture of cooled water droplets and water vapor. The water droplets fall out under the influence of gravity and are recovered as liquid water in a reservoir. The relatively small portion of water vapor, produced in the process, can be either released to the surroundings or recondensed by various means, depending on the requirements of the specific application.

Concluding remarks

This article has been devoted to the basic principles of the new refrigeration method. For more details on commercial applications of the atomizing reactor and related technologies now under development, we refer interested readers to the contact addresses given below.

Most interesting, from a scientific point of view, is the anomaly constituted by the large temperature drop inside the atomizing reactor, as mentioned above – a temperature drop caused by the atomization process itself, before significant evaporation has occurred. Evidently the atomization process itself is able to tap and consume a significant portion of the thermal energy of the water – a circumstance that is confirmed by the curious fact, that the efficiency of the new refrigeration method *increases* with the temperature of the water, whereas that of conventional methods *decreases*. This would seem to indicate that the process of coupling of frequencies, via argumental interactions, extends up into the ultra-high range of frequencies of electromagnetic radiation normally associated with "heat". It thereby points to the need for a far-reaching revision of present conceptions of thermodynamics.

This opens up a vast field for further scientific investigation, which we hope will engage the interest and support of the relevant scientific institutes and researchers.

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