Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 2, Issue 3 / 2017, pp. 22-42

A. Mechanics, Mechanical and Industrial Engineering, Mechatronics

From thermodynamics with finite speed of thermal machines toward biological quantum thermodynamics with finite speed of the cardio-pulmonary system

STOIAN PETRESCU*, BOGDAN BORCILA, MONICA COSTEA, ROMI BOLOHAN, VALERIA PETRESCU, GEORGETA BOTEZ

Thermotechnics, Engines, Thermical and Frigoric Equipment Department, University POLITEHNICA of Bucharest, Romania

Abstract. In this paper we present a synthesis on the epistemological process of the *discovery, invention and construction* of *Quantum Biological Thermodynamics with Finite Speed of the Cardio –Pulmonary System (QBTFSCPS)* starting *from Thermodynamics with Finite Speed Applied to Thermal Machines (TFS).* We present first when and how Thermodynamics with Finite Speed of Thermal Machines was *invented, developed and validated,* and after that we show *how we extended it* to a *Biological – Electrochemical - Thermal Machine*, namely to the *Cardio-Pulmonary System*, creating what we call: *Quantum Biological Thermodynamics with Finite Speed of the Cardio –Pulmonary System (QBTFSCPS).*

Keywords: Thermodynamics with Finite Speed, Cardio - Pulmonary System, Quantum Biological Thermodynamics with Finite Speed

1. Introduction

In the years 1960-1970 Prof. Lazăr Stoicescu (Adviser) and Stoian Petrescu (working for his PhD Thesis [1]) started to develop what they called from the very beginning *Thermodynamics with Finite Speed (TFS)* [1-3], [4-8], based on a *new expression of the First Law of Thermodynamics for Processes with Finite Speed:*

$$\mathrm{d}U = \delta Q_{irrev} - P_{mi}\left(1 \pm \frac{a\,w}{c}\right)\mathrm{d}V \tag{1}$$

where: $a = \sqrt{3k}$; w = average speed of the piston; $c = \sqrt{3RT}$ = average molecular speed.

*Correspondence address: stoian.petrescu@yahoo.com

Equation (1) was published for the first time in [1, 4], and it represents *the starting point of Thermodynamics with Finite Speed (TFS).* Based on it, *all 5 irreversible processes with finite speed have been studied* [5, 6]. New equations for these *irreversible processes* were derived [9-11] and their use in the cycle analysis yielded *the first cycle with finite speed approach*. (Table 1).

An Otto irreversible cycle was studied in 1965 [1, 7] by L. Stoicescu and S. Petrescu, for which the *first expression of the Efficiency of an irreversible cycle with finite speed was proven.*

For all *irreversible cycles with finite speed* studied after that moment (1965) until now (2017) we have tried to get a similar expression, namely:

η_{irrev} = 1- (Classical reversible expression) x (Correction which takes into account the influence of *finite speed w* generating irreversibilities in the cycle)

Here we present the results obtained in 1965 in the paper of L. Stoicescu and S. Petrescu [7], and in S. Petrescu PhD Thesis [1]. (Formulas and figures are original photocopy from paper [1, 7]).

The explicit analytical formula for the Irreversible Otto Cycle with Finite Speed, corresponding to Eq. (2) from [1, 7] is:

$$\eta_{t\,irr} = \left(1 - \frac{1}{\varepsilon^{k-1}}\right)\left[1 - \frac{2\,a \cdot w}{c_1} \cdot \frac{1}{\varepsilon^{\frac{k-1}{2}}\left(\varepsilon^{\frac{k-1}{2}} + 1\right)\left(\lambda^{\frac{1}{2}} - 1\right)}\right] = \eta_{tr} \cdot \eta_{irrev} \tag{2}$$

where:

$$\eta_{irrev} = \left[1 - \frac{2\,a \cdot w}{c_1} \cdot \frac{1}{\varepsilon^{\frac{k-1}{2}}\left(\varepsilon^{\frac{k-1}{2}} + 1\right)\left(\lambda^{\frac{1}{2}} - 1\right)}\right] \tag{3}$$

The original *p-V* diagram (from paper [7]) for the two compared cycles (REVERSIBLE AND IRREVERSIBLE) is presented in “Figure 1”.

Based on Formula (3), in “Figure 3” (original figure from paper [7]) we represented the “Decrease of irreversible Otto Cycle Efficiency with the increase of Average Finite Speed of the piston (w_{med})”.

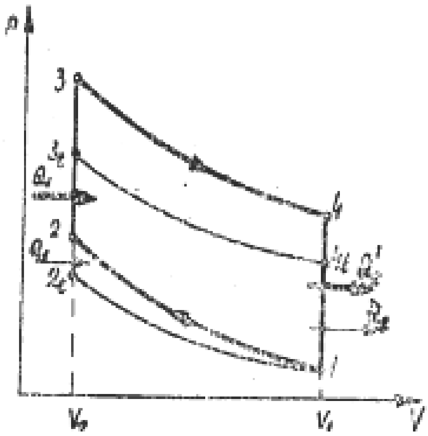

Fig. 1. Otto Cycle p-V Diagram for reversible and irreversible cycles [7].

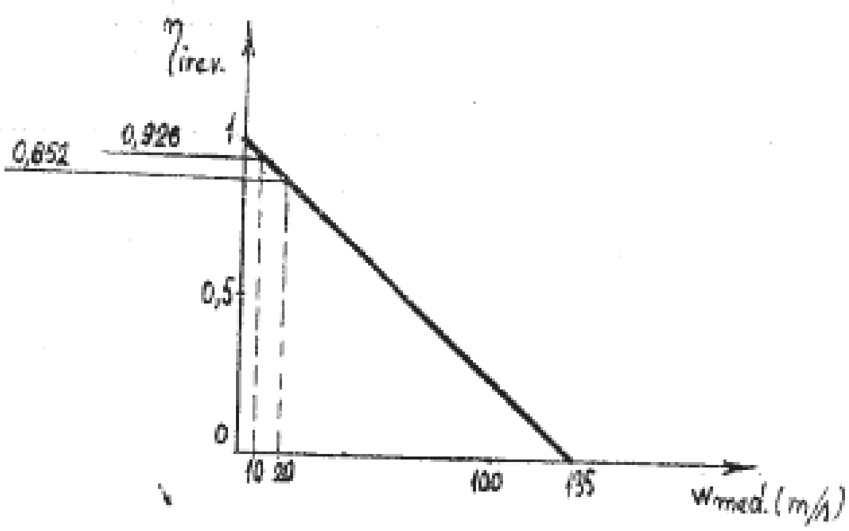

Fig. 2. Decrease of the Otto Cycle Efficiency [7].

The expression of the Maximum Possible Speed of the piston, for the Irreversible Otto Cycle, also determined in [7] was:

$$w_{max} = \frac{c_1}{2\,a} \cdot \varepsilon^{\frac{k-1}{2}} \left(\varepsilon^{\frac{k-1}{2}} + 1\right)\left(\lambda^{\frac{1}{2}} - 1\right) \tag{4}$$

where: k = *adiabatic exponent of the gas* in cylinder; λ = *pressure increase ratio*, during the isometric process 2-3; c_1 = *average molecular speed* in the initial state 1; a = $(3k)^{½}$; ε = *compression ratio* = V_1/V_2.

In all our papers written after 1965 (by S. Petrescu with his Ph.D Students and coworkers), where we studied the *Efficiency* of *Real Irreversible Cycles in the framework of Thermodynamics with Finite Speed,* we have used *the same pattern of the analytical formula of Efficiency* (for Engine cycles) or COP (for Refrigeration and Heat Pump cycles) as in formula (2), namely a product between the ideal (reversible cycle) efficiency, η_{rev} and a parenthesis depending on the speed *w* and other constructive and functional parameters like λ and ε [12-23].

For all irreversible cycles studied after that moment (1965) until now (2017) using the *Direct Method from Thermodynamics with Finite Speed* (TFS) (we *invented and constructed systematically*) we have tried to get a similar expression, namely:

$$\eta_{t,it} = \eta_{rev} \,.\, \eta_{irrev}(w, \textit{other parameters of the cycle})$$

After many years, in 1992, Eq. (1) was extended by Petrescu, S., Stănescu, G., Iordache, R., Dobrovicescu, [24] *to irreversible processes with Finite Speed, Friction and Throttling,* obtaining the equation:

$$\mathrm{d}U = \delta Q_{irrev} - P_{mi}\left(1 \pm \frac{a\,w}{c} \pm \frac{f \cdot \Delta P_f}{P_{mi}} \pm \frac{\Delta P_{thr}}{P_{mi}}\right)\mathrm{d}V \tag{5}$$

Table. 1. The equations of all 5 irreversible processes [11].

How do we compute irreversible processes?					
Process	$m = ?$	$P_2, V_2, T_2 = ?$	$\Delta U, \Delta H = ?$	$W_{12} = ?$	$Q_{12} = ?$
Izobaric $P = const$	$m = \frac{P_1V_1}{RT_1}$	$P_2 = P_1$, V_2 given $\frac{T_1}{V_1} = \frac{T_2}{V_2}$	$\Delta U = m\, c_v \Delta T$ $\Delta H = m\, c_p \Delta T$	$W_{12,P} = p_1 (V_2 - V_1)\, \gamma$	$Q_{12,P} = \Delta H = m\, c_p \Delta T\, \gamma_Q$
Isometric $V = const$	$m = \frac{P_1V_1}{RT_1}$	$V_2 = V_1$, T_2 given $\frac{P_1}{T_1} = \frac{P_2}{T_2}$	$\Delta U = m\, c_v \Delta T$ $\Delta H = m\, c_p \Delta T$	$W_{12,V} = 0$	$Q_{12,V} = \Delta U = m\, c_v \Delta T$
Isothermal $T = const$	$m = \frac{P_1V_1}{RT_1}$	$T_2 = T_1$, V_2 given $P_1V_1 = P_2V_2$	$\Delta U = 0$ $\Delta H = 0$	$W_{12,T} = P_1V_1 \ln\frac{V_2}{V_1}\beta$	$Q_{12,T} = W_{12,T}$ $= P_1V_1 \ln\frac{V_2}{V_1}\beta$
Adiabatic $\delta Q_{rev} = 0$ $S = const$ $dS = \frac{\delta Q_{rev}}{T}$	$m = \frac{P_1V_1}{RT_1}$	$P_1V_1^k = P_2V_2^k\frac{\alpha_2}{\alpha_1}$; $T_1V_1^{k-1} = T_2V_2^{k-1}\frac{\alpha_2}{\alpha_1}$ $\frac{T_1}{P_1^{\frac{k-1}{k}}} = \frac{T_2}{P_2^{\frac{k-1}{k}}}\left(\frac{\alpha_2}{\alpha_1}\right)^{\frac{1}{k}}$	$\Delta U = m\, c_v \Delta T$ $\Delta H = m\, c_p \Delta T$	$W_{12,ad} = \frac{P_1V_1 - P_2V_2}{k-1}$ $= -\Delta U = mc_v \cdot (T_1 - T_2)$	$Q_{12,ad} = 0$
Polytropic $n = const$	$m = \frac{P_1V_1}{RT_1}$	$P_1V_1^n = P_2V_2^n$; $T_1V_1^{n-1} = T_2V_2^{n-1}$ $\frac{T_1}{P_1^{\frac{n-1}{n}}} = \frac{T_2}{P_2^{\frac{n-1}{n}}}$	$\Delta U = m\, c_v \Delta T$ $\Delta H = m\, c_p \Delta T$	$W_{12,pol} = \frac{P_1V_1 - P_2V_2}{n-1}$	$Q_{12,pol} = \Delta U + W_{12,pol}$ $= m\, c_v \Delta T + \frac{P_1V_1 - P_2V_2}{n-1}$
$k = 1.66$ (m. a.) $k = 1.4$ (d. a.) $k = 1.3$ (t. a.)		Ideal / Perfect gas, closed system			$H = U + PV$
		$c_v = \frac{R}{k-1}, c_p = \frac{kR}{k-1}$	$c_{v,av}$, $c_{p,av}$ from tables	$m = const$	$R = \frac{R_U}{M}$, $R_U = 8314$ J/(kmol·K)
Irreversible adiabatic process corrections	$\alpha_1 = \left(1 \pm \frac{aw}{c_1}\right)^2; c_1 = \sqrt{3RT_1}; a = \sqrt{3k}$ $\alpha_2 = \left(1 \pm \frac{aw}{c_2}\right)^2; c_2 = \sqrt{3RT_2}; a = \sqrt{3k}$		$\beta = \left(1 \pm \frac{aw}{c_T}\right)$ ← Irreversible isothermal process correction $\gamma = \left(1 \pm \frac{aw}{c_{12,av}}\right)$; $c_{12,av} = \frac{c_1 + c_2}{2}$ ← Irreversible isobaric correction $\gamma_Q = \left(1 \pm \frac{aw}{c_{12,av}} \cdot \frac{W_{12,rev}}{\Delta H}\right)$ ← Irreversible isobaric correction for heat		

In 1994 S. Petrescu and C. Harman published the paper [25]. In this paper based on [24] has been introduced/invented the *Direct Method*. This more complete Equation (5) was essential for the development of TFS to the level of introducing/inventing the Direct Method [25-31], *for the study of any irreversible process with finite speed, throttling and friction.* The most important achievement of this new method that we called the *Direct Method* is the *Scheme of Computation of Efficiency and Power* of Stirling Machines *that was validated for 12 Stirling Engines* [30]. After this achievement of TFS, as *a new branch of Irreversible Thermodynamics*, researchers started to use this new method all over the world [32-37].

The *Direct Method* was used for Solar Stirling Motors [38, 39] and for Stirling Engines included in *Micro-Power Solar Systems* for heating and electricity production [40], obtaining *a new Validation using the same two adjusting parameters introduced in the previous validation for 12 engines* [9,10, 25, 30, 38, 39, 41-44]. This was an important moment in recognizing the *Direct Method* as a

very powerful method *for computing Efficiency and Power of Thermal Machines' irreversible cycles.*
The *Direct Method* was also used in the Refrigeration Machines' study [29, 40, 44] leading to analytical expressions for COP and Power consumption, as well as for the Isentropic Efficiency of the Vapor Compressor, part of a Refrigeration Machine. The Validation of the Computation Scheme for Refrigeration Machines was also achieved. This is an important result, because as far as we know, analytical expressions for these performance have not been previously reported. Even for perfect gas compressors (much simpler to treat than vapor compressors) an analytical expression for Isentropic Efficiency does not exist yet.
Furthermore, in a similar way as for Stirling Machines, Optimization of Refrigeration Machines and Heat Pumps became possible, providing the optimum operation speed, highly accurate due to validation. Such achievements have not been obtained by any other branch of Irreversible Thermodynamics (Onsager-Prigogine's Phenomenological Linear Irreversible Thermodynamics, Curzon-Ahlborn's Thermodynamics with Finite Time, Exergetic Method, Entropic Method), despite of their success. Recently we have tried the *Unification of Thermodynamics with Finite Speed with Thermodynamics with Finite Time* [45]. Encouraged by the above mentioned achievements, new extensions of Thermodynamics with Finite Speed and the Direct Method to other domains, different from traditional Thermal Machines, were sought. The first one was in the field of Electrochemical Devices (Fuel Cells, Electrolysers and Batteries) [10, 11, 16, 17, 26, 39, 46-51]. As many (if not all) biological systems are in fact *Electrochemical Machines-Devices* we tried to use TFS in the study of the most important biological system of human being (and mammals), namely the *Cardio-Pulmonary System.* A first step in this direction was already performed [11. 45, 52-56].
The present paper is a continuation of efforts towards the *extension of TFS to Biological Systems.*

2. New concepts and parameter of state

In recent works [11, 57, 58] we have introduced a new concept for Irreversible Thermodynamics of Biological Systems: the *Stationary State* which characterizes the *dynamical state of the two components* (Sub-systems) of the Cardio-Pulmonary System. We do consider that in a similar manner to quantum mechanics discovered by Planck (1900) for atoms and molecules, the *frequency of oscillation* is an essential parameter of state, correlated with the *energy* in the well-known equation:

$$Energy = h \cdot Frequency, \qquad (h = \text{Planck's constant}) \tag{6}$$

For the macroscopic system comprising two oscillating sub-systems (Heart and Lungs), frequency will also play an important role as a *parameter of state* for what we called *Stationary States*. The two frequencies involved are: F_H = the Heart's *Frequency* of oscillation (usually called "pulse" or "heart beat") and F_L = the

Lungs' *Frequency* of breath. During the day or in the night, the two frequencies are constant in what we called *"Stationary States"* (i.e., for minutes, tens of minutes or even hours while sleeping). Otherwise, when passing from one stationary state to another stationary state both of these frequencies vary. Nevertheless, one of these frequencies could be constant in a certain process. This is similar to the situation of two Thermal Machines connected in a certain way, each of them being in fact a subsystem of the Ensemble of two oscillating machines.

From our thermodynamic point of view we consider the Heart as a pump for liquid (blood) and the Lungs as two compressors (connected in parallel in-between, but in series with the "right side" of the Heart). The "left side" of the Heart is connected in series with the rest of the body (internal Organs, Brain, Muscles etc.).

The two parameters of stationary state, F_H and F_L, are already used in Physiology and in Medical practice as two extremely important parameters that characterize the state of health or pathology of a human being. There are a lot of devices used for getting these parameters: pulse meters, EKG-devices, Holters (for EKG), spirometers, and monitoring devices in Emergency rooms or Hospitals.

The novelty brought by our approach consists in the concept of *Ratio of these two frequencies,* $R_f = F_H / F_L$ *that will represent the interactional parameter of state* between the two sub-systems, Heart and Lungs. This idea was generated during the study of the two oscillating pistons Stirling Machine. In the *Computation Scheme of Efficiency and Power for Stirling Machines* [30] validated in TFS, it was essential to find a correlation between the speeds of the two pistons, together with the speed of working fluid (the gas) passing through the Regenerator. Only after solving the problem of these three speeds correlations, the Efficiency and Power could be derived as analytical functions of only one speed, that of the working piston, *w,* present also *in the equation of the First Law for Processes with Finite Speed* **(**Eqs. (1) and (2)).

For the *Cardio-Respiratory System* we did the same, namely we tried to find a correlation between the *speed of the Heart* = F_H, and the *Speed of the Lungs* = F_L. The speed of the blood in vessels is already used in Physiology as an important parameter which determines the friction losses and contributes to the increase of Maximum Heart Pressure = P_{max}.

The newly introduced parameter of the *Stationary State of interaction* between the Heart and Lungs is the *Frequency Ratio*:

$$R_f = F_H / F_L \tag{7}$$

The experimental study of this new parameter of state, together with the other two: F_H, and F_L, has led to invent/introduce similar diagrams to those of Classical Thermodynamics, namely: *P-V, T-S, h-S, U-S*.

Thus, 5 diagrams were introduced [57]:

$F_H = f(F_L)$; $F_L = f(F_H)$; $R_f = f(F_L)$; $R_f = f(F_H)$, and

F_H, F_L, R_f as function of time t.

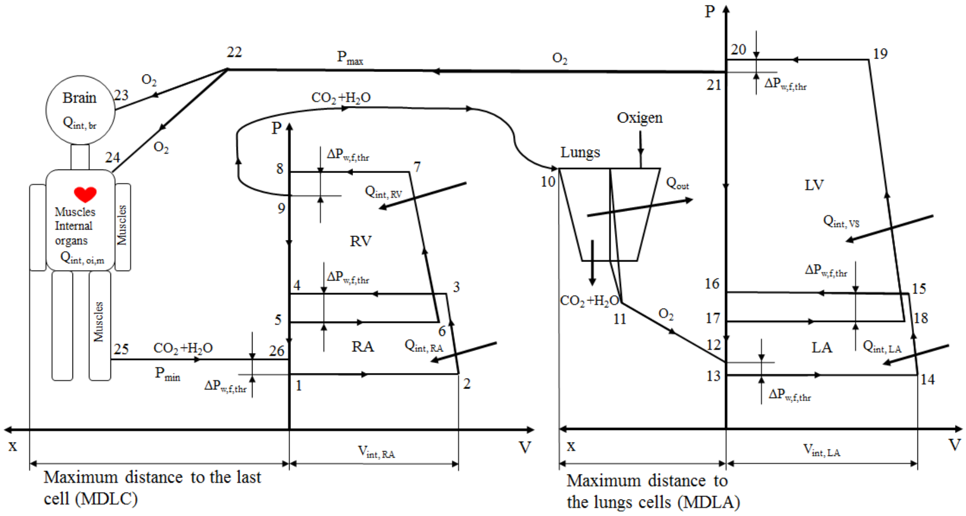

Fig. 3. *PV/Px* Diagram for Cardio-Respiratory-Vascular System.

Using these diagrams and the *PV/Px* diagram from Fig. 1 (similar with that introduced for Stirling Machines), we intended to obtain *analytical expressions for Efficiency and Power of the Cardio-Respiratory System*, as we did for Stirling Machines [30] and for vapor compressors [40]. Lungs are two *air compressors* (containing also water vapor and CO_2) and the *Heart is the pump for a liquid (blood)* with variable viscosity (as function of temperature and composition).
In previous paper [57] we studied the correlation between these 3 parameters of *stationary state* in the above diagrams for 50 persons and with thousands of experiments, and we discovered that between them exists a *quantized correlation:*

$$F_H = F_L\left(2 + \frac{N}{4}\right) \tag{8}$$

Equation (8) introduces a new parameter (integer number), N, which characterizes the level of interaction between the two oscillating subsystems, Heart and Lungs.
As *N* is an *integer number*, we called Eq. (8) *the quantum equation of the Interactional State of the Heart - Lung System in Stationary States.*
Anyone can draw such a graph by measuring the frequency F_H *(his pulse)* and F_L (*his breath's rhythm*) in stationary states, all day long. Then, by using Eq. (8) one can get *N* and build the graph (Fig. 4).
This graph is a sort of mechanical equivalent of EKG, as it shows how "good" or "bad" the *Heart - Lungs Interaction* is functioning. It could help a person with high probability of fibrillation to take precautions, and be prepared when fibrillation occurs.
When estimating the importance of this work we should note that 6 million persons with fibrillation are estimated in the EU. In the case of ventricular fibrillations every minute counts, before reaching the hospital emergency room. Moreover, if

the treatment is not fast enough and well administrated, the defibrillation is an expensive and not always successful procedure.

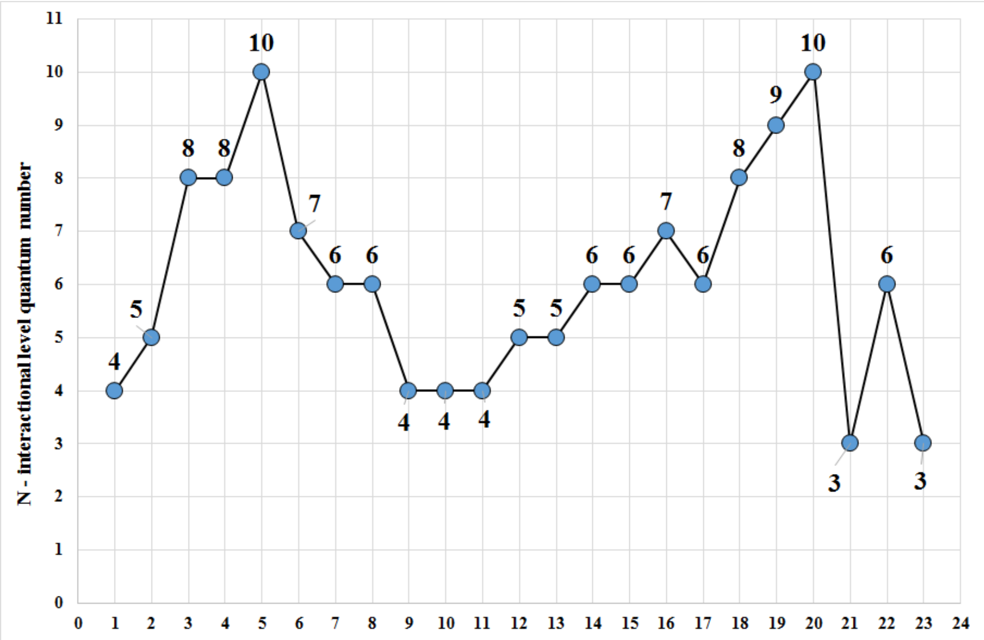

Fig. 4. Quantum Interaction Number *N* as a function of day time *t* (SP, April 2015).

A recently invented and already commercialized (in the USA) device can be used, worn as a belt, for the early detection of such probability. For those not affording to buy such a belt, the graph from and built by themselves (by just measuring F_H and F_L), could make them aware about an imminent fibrillation risk.
Ultimately, this potentially lifesaving procedure can be produced into an easy to use software application incorporated in modern health suites available on most Smartphones.

3. The structure of quantum biological thermodynamics of the cardio-respiratory system

Any process between two stationary states, in a similar way like in Classical Reversible (Equilibrium) Thermodynamics (CRT) will obey to *the equation of state*: $Pv=RT$
The similarity is even formal:

$$R = Pv/T \tag{9}$$

From Clausius formula for the average speed of the molecules:

$$c = \sqrt{3RT} \tag{10}$$

it results:

$$T = \frac{c^2}{3R} \tag{11}$$

where T is the *Energy per liberty degree of translation*.

Actually, Eq. (9) shows R as a ratio between two *energetic properties*, namely, Pv - *Displacement Work* and T - *Energy per translation liberty degree = Temperature*)

In a similar way, R_f *is the ratio of two energetic quantities, as in Plank's equation, where the energy is correlated with the frequency*. *The Power of the Heart* and the *Power of the Lungs* are also proportional to the corresponding frequencies of oscillation of the two subsystems of the Cardio-Pulmonary System.

Steps completed in the invention and then build of TFS in a similar way with CRT will be followed in introducing what we call *Quantum Biological Thermodynamics of Cardio-Respiratory System*. Its structure consists of:

1 - Introducing the parameters of Stationary States: F_H, F_L, R_f.

2 - Looking for an *Equation of stationary states*, similar to the equation of state form $Pv=RT$, which turns out to be quantized - similar to quantum mechanics of Hydrogen or any atom (also composed of two oscillating subsystems: nucleus-protons, and electrons), and finding (8) [59].

This discovery is the *essence* of this new branch of Thermodynamics with Finite Speed for Cardio-Pulmonary Systems.

3 - Using the 3 parameters of stationary states, then (8), and introducing 5 diagrams to show the states of the system.

4. Using these 5 diagrams for showing the processes in-between two and more stationary states, similar to the processes and cycles described in thermodynamic diagrams: *p-V*, *T-S*, *h-S*, *U-S* etc.

5. Inventing a diagram which describes the interaction of the Cardio-Respiratory System with the rest of the organism: the *PV/Px* diagram.

6. Studying the processes by using these diagrams for determining analytical expressions for the Efficiency and Power of Heart and Lungs, and for the entire Cardio-Respiratory System, in interaction with the whole body.

In the previous papers [57, 58] steps 1-4 were already made. Here we move ahead to steps 4-6.

The already introduced [57] *PV/Px* diagram is used in this paper, in connection with the equation of the *polytropic process* to show that the analytical expressions of Efficiency and Power can be obtained as functions of only one speed, either F_L or F_H as they are connected by (7), the equation of stationary state.

Any final expressions of the Power and Efficiency will lead to the computation of the *Entropy Source,* $\Delta S/\Delta t$, and the possibility of an irreversibility study in the same manner as in TFS for Thermal Machines, using the equation of the First Law for processes with finite speed (Eqs. (1) and (2)).

From now on, such expressions will provide to the designers of Artificial Hearts and Artificial Lungs (Teams of Engineers, Medical Doctors and Physiologists) a powerful tool for *Optimization Design*, personalized for each category of persons: kids, young, mature, and old persons.

4. Efficiency and power equations

4.1. Power

Using the diagram from Fig. 3, we can express the Power of the heart, as in the Thermodynamics with Finite Speed (by taking into account the throttling losses through valves):

$$Power_{heart} = F_H \left(W_{RA} + W_{RV} + W_{LA} + W_{LV}\right) \tag{12}$$

where: W_i are the atrium and ventricle work (right and left).
Combining Eq. (12) and (8) it results:

$$Power_{Heart} = F_L \left(2 + \frac{N}{4}\right)\left(W_{RA} + W_{RV} + W_{LA} + W_{LV}\right) \tag{13}$$

Equation (13) shows that the Power of the heart is also a quantized quantity, N being always an integer in normal stationary states. In case of illness, by atrial or ventricular fibrillation for example, the stationary states are not achieved anymore, and a chaotic, much disorganized functioning of the heart appears. The flow rate of the blood is affected dramatically and, as a consequence, the oxygen flow rate to the whole body diminishes dramatically.
The work done by the right side of the heart is:

$$W_R = W_{RA} + W_{RV} = \left(P_3 - P_2\right)V_{in,RA} + \left(P_7 - P_6\right)V_{in,RV} = \left(P_3 - P_2 + P_7 - P_6\right)V_{in,R} \tag{14}$$

For: $V_{in,RA} = V_{in,RV} = V_{in,R}$ and $P_3 - P_6 = \Delta P_{\text{int},R}$ one gets:

$$W_R = W_{RA} + W_{RV} = \left(P_7 - P_2 + \Delta P_{\text{int},R}\right)\cdot V_{in,R} \tag{15}$$

where: $\Delta P_{int,R}$ = f (F_H), as in TFS for compressors and pumps.
Furthermore, by using Eq. (8) to get F_H as function of F_L, all throttling losses in the valves of the heart will be expressed as function of only one speed, namely, F_L:

$$\Delta P_{\text{int},R} = f\left(2 + \frac{N}{4}\right) \tag{16}$$

The work done by the right side of the heart is:

$$\begin{aligned} W_L &= W_{LA} + W_{LV} = \left(P_{15} - P_{14}\right)V_{in,LA} + \left(P_{19} - P_{18}\right)V_{in,LV} = \\ &= \left(P_{15} - P_{14} + P_{19} - P_{18}\right)V_{in,L} \end{aligned} \tag{17}$$

and as: $P_{15} - P_{18} = \Delta P_{thr,LV}$, Eq. (17) becomes:

$$W_L = \left(P_{19} - P_{14} + \Delta P_{thr,LV}\right)V_{in,L} \tag{18}$$

Finally the heart work is:

$$W_{Heart} = W_L + W_R = \left(P_{19} - P_{14} + \Delta P_{thr,LV}\right)V_{in,L} + \left(P_7 - P_2 + \Delta P_{\mathrm{int},R}\right)V_{in,R} \tag{19}$$

In a similar way the Power for the Lungs will be computed as:

$$Power_{Lungs} = 2\,F_L \cdot W_{Lung} \tag{20}$$

where:

$$W_{Lung} = \Delta P_{Lung} \cdot \Delta V_{Lung} \tag{21}$$

At the internal combustion engines, the pressure drop during air admission and burned gases evacuation $\Delta P_{adm\text{-}ev}$ may be expressed as a function of the shaft's rotation speed or of the piston speed. As for the lungs, the pressure loss during inspiration and expiration, responsible for the Power consumption of the lungs, is function of the speed of the lungs F_L:

$$\Delta P_{Lung} = f\left(F_L\right) \tag{22}$$

and the *Lungs Power consumption* becomes:

$$Power_{Lungs} = 2\,F_L \cdot W_{Lung} = 2\,F_L \cdot \left\lfloor \Delta P_{Lung}\left(F_L\right)\right\rfloor \cdot \Delta V_{Lung} \tag{23}$$

Finally, the *Total Power consumption* of the Cardio-Pulmonary System is:

$$Power_{total} = Power_{Heart} + Power_{Lungs} = f\left(F_L\right) \tag{24}$$

Equation (24) gives the total power consumption as function of only one speed, namely the speed of the Lungs, F_L.

One notes, also, a very important feature from the point of view of TFS, namely the power consumed by the Heart is not only function of the pressure usually measured on blood vessels, but is also dependent on the pressure drops in all 6 valves of the heart. The malfunction of the heart valves is linked to important illnesses similar to the fluttering phenomenon of the compressor valves that appears at very high speed with devastating effects as the flow rate drops to zero, despite a lot of work/power is consumed.

4.2. Efficiency and Polytropic Processes

Two new concepts are introduced for the heart, namely:

Relative efficiency in a process of change of stationary state, defined by the ratio of the Heart Power in the stationary state 2, divided to the Power in the initial stationary state 1.

Absolute Efficiency is the ratio of the Power in a certain *stationary state* (day or night) to the *Power in the fundamental stationary state* (in the morning, immediately after *wake up*).

As previously seen, the *pressure drops* in the valves of the heart ΔP_v increasing with F_H, the *Power consumption* will increase, and *Efficiency* will decrease, as it is also happens with the *compressor isentropic efficiency* [40]. Figure 4 illustrates the stationary states and processes between successive stationary states measured during a day by SP (April 2015).

Based on the data from tens of such figures one can conclude that each process can be considered as a *polytropic process, with* the *polytropic coefficient* being given by the *slope of the process line*:

$$\mu = \frac{\Delta N}{\Delta F_L} \tag{25}$$

The similarity between Eq. (25) and the *polytropic coefficient definition* from *Classical Reversible Thermodynamics* (CRT) consists of the fact that both correlate properties in the initial state with properties in the final stationary state of the process via a coefficient.

In Figure 4 many processes having the same slope can be observed. Based on statistical data from different days one can obtain the probability to have a certain slope for each possible elementary process: raising up of the bed, sitting on a chair, directly standing up from bed, or the opposite, sitting on a chair, or laying on bed (from vertical to horizontal position). These processes of *position change* in the gravitational field consume different energies in order to accomplish the process and then, to maintain the new position. In fact, other muscles are involved in these 3 states: more in the vertical position than in the horizontal one. Thus, the power consumed by the heart and lungs is very different in these 3 points, less in the horizontal than in the vertical one. The *Frequency's* F_H and F_L will correspondingly change in these processes.

Other processes can be also monitored, such as “eating” breakfast, lunch or dinner, walking, climbing or descending the stairs or a hill, moving fast (“eating” breakfast, lunch or dinner, walking, doing gymnastics, doing repetitive physical work etc.

For all these type of elementary process, a distribution of slopes in *polytropic processes* can be statistically estimated for any person. Actually, values of μ between $(-\infty, +\infty)$ result, as in the case of *polytropic exponent n* from CRT.

Based on such data a validation of Eq. (25) can be obtained, similarly to the performances of Thermal Machines obtained on the test bench, or in real operation condition.

These data can be used by designer teams of artificial hearts (medical doctors, mechanical and electrical engineers, physiologists) or lungs, with personal data, obtained with some tests, before the patient becomes very ill, in order to implant a *proper heart-suited for each person*, as it is done when replacing parts of an engine. It is obvious the one cannot use parts from a car-engine (i.e., Dacia) to another type of car-engine (Toyota). Things are similar for different persons. With other word *artificial heart* manufacturing should take into account some fundamental characteristics of different persons (age, sex, height, weight, etc.)

In Fig. 5, the following processes with the same slope can be identified:

● The lines: 0-1; 15-16; 8-9; 11-12; 21-22; 22-23 represent ”*iso-respir processes*”, with F_L = constant.

● The lines: 2-3; 9-10; 12-13 represent ”*iso-quantum number processes*”, with N = constant.

● The line 4-5, and 17-18 have the same slope. We call them *“polytropic processes with the same slope”:* $(\Delta N / \Delta F_L) = 4/2 = 2$.

● The process 20-21 has almost the same slope (7/3= 2.33) as the line 4-17.

● The lines 18-19; 5-6; 16-17; 13-14 have all the same slope: 2/4= 0.5.

Starting from experimental measurements of F_H and F_L, the connection between the *slope of polytropic process* and the *change of position* (from horizontal to vertical position, or from sitting on a chair to standing position, for example) or other *processes generated by activities* (eating, walking, running, raising up on stairs or on hill) may be established and also, the Power consumption and Efficiency of such processes may be calculated by relations similar to those used for the polytropic process in the Classical Reversible Thermodynamics.

The polytropic equation will be:

$$F_{H2} = F_{L2} \cdot \left(2 + \frac{N_1}{4} + \mu \frac{F_{L2} - F_{L1}}{4} \right). \tag{26}$$

By Equation (26) the *Power of the heart* results *as function only of* F_p, similarly to the computations of the cycles in Thermal Machines. One can compute the daily Total Energy Consumption of the Heart – Lungs System and comparing the values for different days, establish the corresponding personal effort.

This could lead to searching ways of life style improvement in order to protect the heart of the excessive stress that could affect the personal health and life. One notes that the normal values of the heart frequency F_H considered the past 10-15 years as between 60 and 100 oscillations / minute, have been recently restricted by EU to the healthier domain, 60 - 90. The graph from Fig. 5 could also help better organize life, so that more time could be spent in the normal domain of F_H with less effort for the Heart.

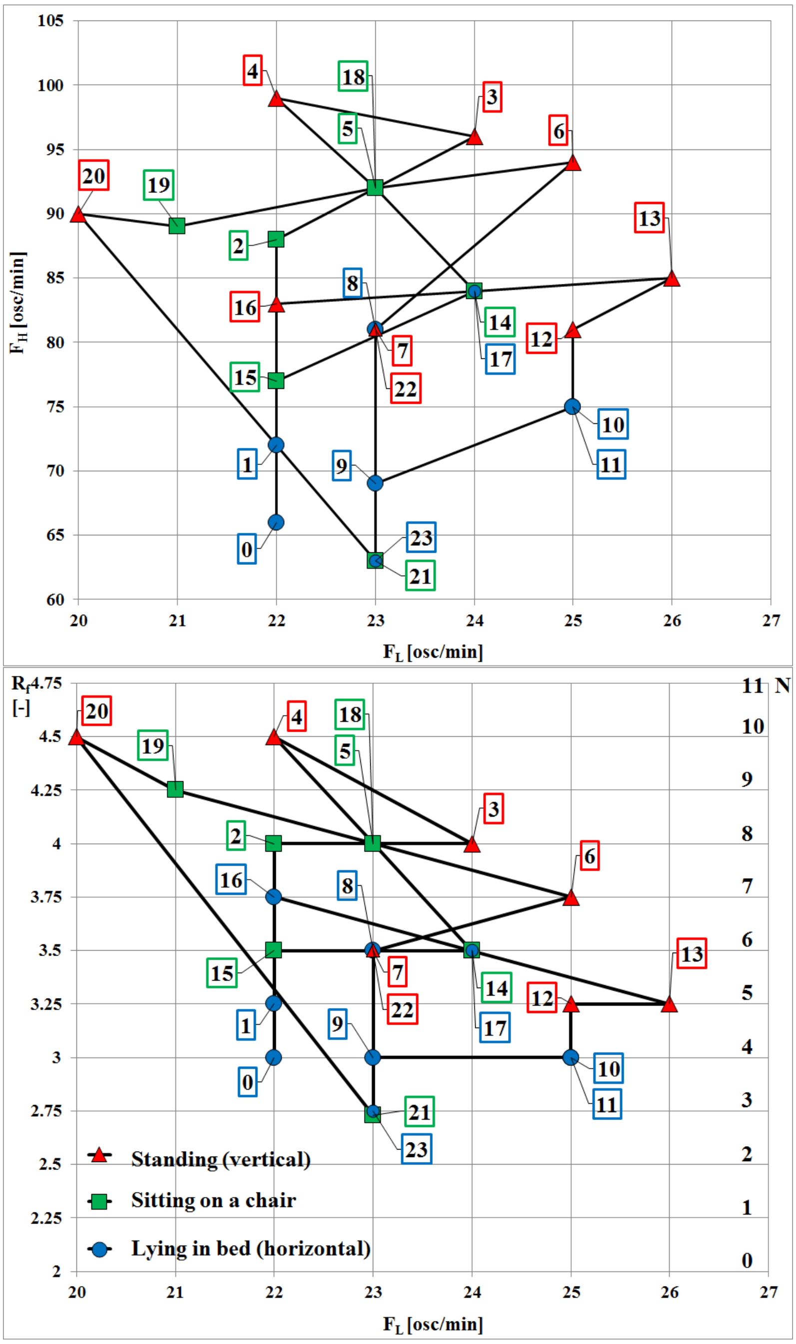

Fig. 5. Diagrams representing F_H = f(F_L) and R_f = f(F_L) and N = f(F_L) for *Processes between Quantum Stationary States* in the Cardio-Respiratory System (for SP).

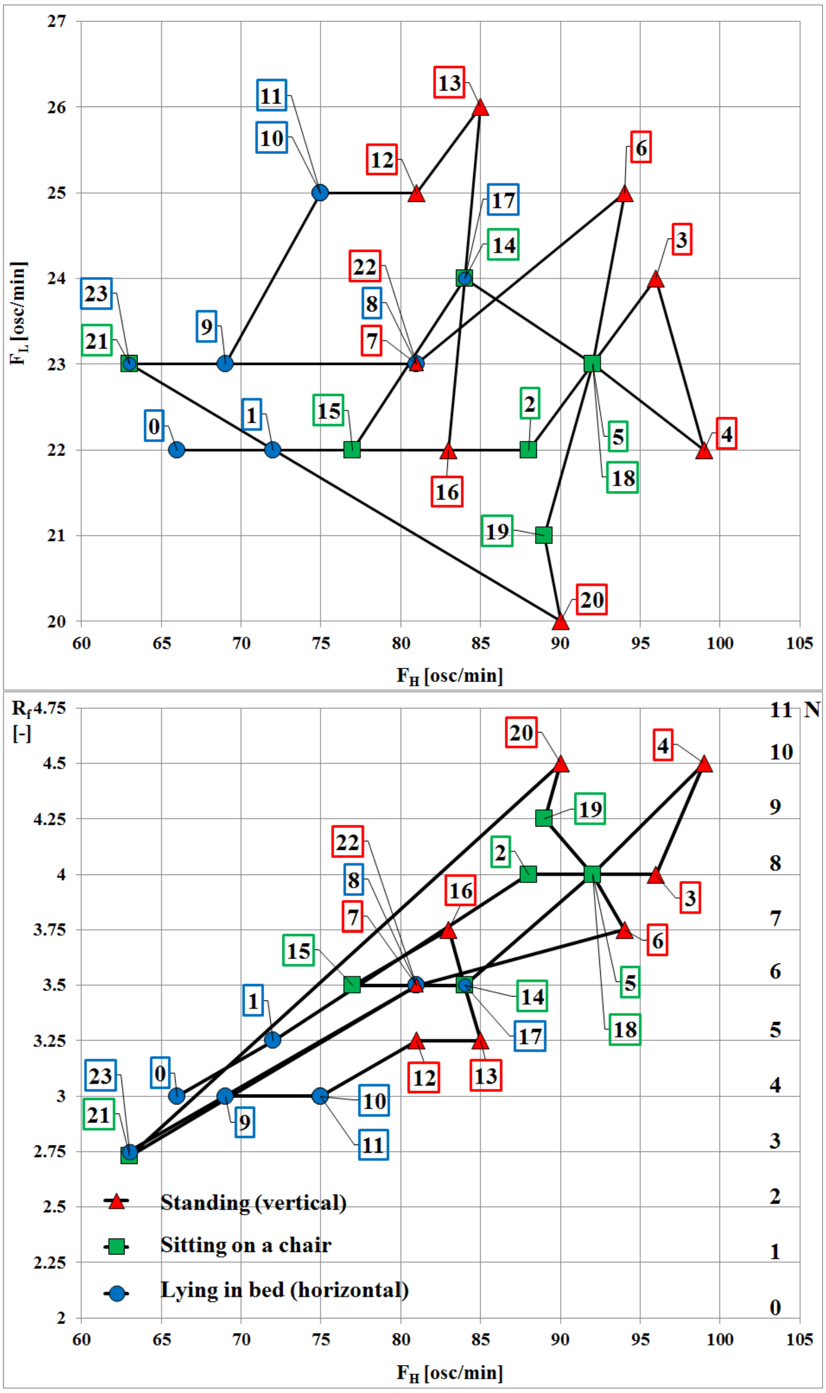

Fig. 6. Diagrams representing F_L = f(F_H) and R_f = f(F_H) and N = f(F_H) for *Processes between Quantum Stationary States* in the Cardio-Respiratory System (for SP).

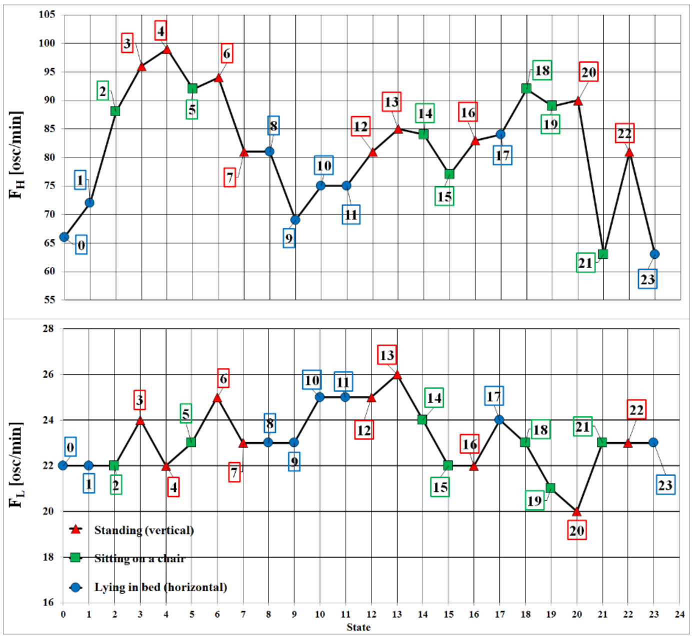

Fig. 7. Diagrams for F_H and F_L regarding the stats of the measurements for *Processes between Quantum Stationary States* in the Cardio-Respiratory System (for SP).

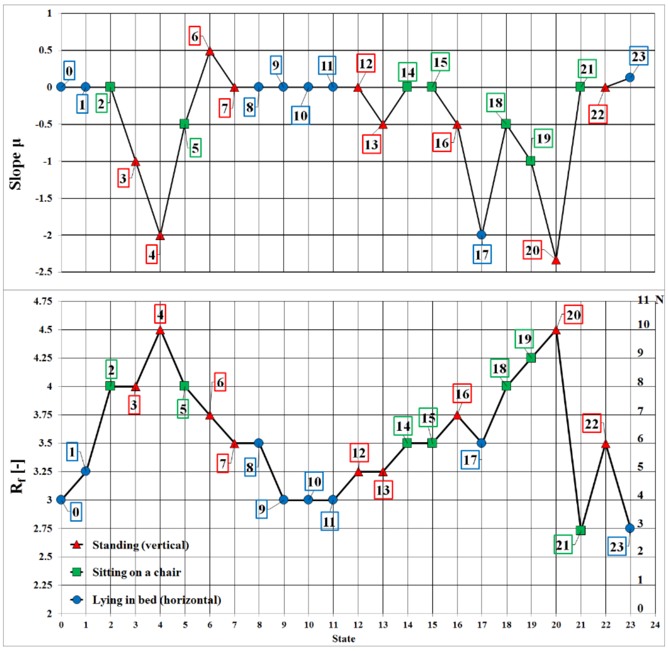

Fig. 8. Diagrams representing the slope and $R_f = f(F_L)$ and $N = f(F_L)$ for *Processes between Quantum Stationary States* in the Cardio-Respiratory System (for SP).

5. Conclusions

The extension of TFS to Biological System is a very ambitious effort that merits to be completed given its important theoretical and practical consequences.
The present paper used the essential discovery of quantization the interaction between Heart and Lungs Frequency, obtaining finally expressions of Heart Power and Lungs Power (Total Power of Cardio-Pulmonary System) as a function of only one speed, F_L.
The results of the experimental study are extremely important, because they could help in Personalized Design of artificial Heart and Lungs for different categories of persons: children, young, mature, old person.
Two interesting diagrams (Fig.4 and 5) are suggested to be built by any person interested in the health status of its Cardio-Pulmonary System. Costless these can show how good or how bad the personal Heart-Lungs interaction is or worn on the bad perspective of fibrillation or other heart diseases (malfunction of the valves, arrhythmia, fluttering). Therefore, precautions could be taken in time, in order to prevent bad or even fatal accidents.

References

[1] Petrescu, S., (Adviser: L. Stoicescu), *Contribution to the study of thermodynamically non-equilibrium interactions and processes in thermal machines*, Ph.D. Thesis, I.P.B., Bucharest, Romania, 1969.
[2] Petrescu, S., *An Expression for Work in Processes with Finite Speed based on Linear Irreversible Thermodynamics,* Studii si Cercetari de Energetica si Electrotehnica, Acad. Romana, 19, 2, 249-254, 1969.
[3] Petrescu, S., *Kinetically Consideration Regarding the Pressure on a Movable Piston*, Studii si Cercetari de Energetica si Electrotehnica, Academia Romana, 21, 1, 93-107, 1971.
[4] Stoicescu, L., Petrescu, S., *The First Law of Thermodynamics for Processes with Finite Speed, in Closed Systems*, Bulletin I.P.B., Bucharest, Romania, XXVI, 5, 87-108, 1964.
[5] Stoicescu, L., Petrescu, S., *Thermodynamic Processes Developing with Constant Finite Speed*, Bull. I.P.B. Romania, XXVI, 6, 79-119, 1964b.
[6] Stoicescu, L., Petrescu, S. *Thermodynamic Processes with Variable Finite Speed*, Buletin I.P.B., Romania, XXVII, 1, 65-96, 1965.
[7] Stoicescu, L., Petrescu, S., *Thermodynamic Cycles with Finite Speed*, Bulletin I.P.B., Bucharest, Romania, XXVII, 2, 82-95, 1965.
[8] Stoicescu, L., Petrescu, S., *The Experimental Verification of The New Expression of the First Law for Thermodynamic Processes with Finite Speed*, Bull. I.P.B., Bucharest, XXVII, 2, 97-106, 1965.
[9] Petrescu, S., Zaiser, J., Petrescu, V., *Lectures on Advanced Energy Conversion*, Bucknell University, Lewisburg, PA, USA, 1996.

[10] Petrescu, S., Harman, C., Costea, M., Florea, T., Petre, C., *Advanced Energy Conversion- Vol I*, Bucknell University, Lewisburg, PA-17837, USA, 2006b.

[11] Petrescu, S., Costea M., Feidt M., Ganea I., Boriaru, N., (Editors), *Advanced Thermodynamics of Irreversible Processes with Finite Speed and Finite Dimensions*, Editura AGIR Publishing House, Bucharest.

[12] Costea, M., (Advisers: S. Petrescu and M. Feidt), *Improvement of heat exchangers performance in view of the thermodynamic optimization of Stirling Machine; Unsteady-state heat transfer in porous media*, Ph.D. Thesis, UPB & U.H.P. Nancy 1, 1997.

[13] Florea, T., (Adv: S. Petrescu), *Grapho-Analytical Method for the study of the operating processes irreversibility in Stirling Engines*, Ph.D. Thesis, UPB, 1999.

[14] Florea, T., Petrescu, S., Florea, E., *Schemes for Computation and Optimization of the Irreversible Processes in Stirling Machines*, Edit. Leda&Muntenia, Constanta, România, 2000.

[15] Petre (Stanciu), C., (Advisers: S. Petrescu, M. Feidt, A. Dobrovicescu), *Utilizarea Termodinamicii cu Viteza Finita in Studiul si Optimizarea ciclului Carnot si a Masinilor Stirling*, U.H.P. Nancy - U.P Bucureşti, Teza de Doctorat, 2007.

[16] Petrescu, S., Maris, V., Costea, M., Boriaru, N., Stanciu, C., *Dura, I., Comparison between Fuel Cells and Heat Engines. I. A Similar Approach in the Framework of Thermodynamics with Finite Speed*, Revista de Chimie, 64, 7, 739-7461, 2013.

[17] Petrescu, S., Maris, V., Costea, M., Boriaru, N., Stanciu, C., Dura, I., *Comparison between Fuel Cells and Heat Engines. II. Operation and Performances*, Revista de Chimie, 64, 10, 1187-1193, 2013.

[18] Petrescu, S., Stanescu, G., *The Direct Method for studding the irreversible processes undergoing with Finite Speed in closed systems*, Rev. Termotehnica, 1, Editura Tehnica, Bucureşti, România, 1993.

[19] Petrescu, S., *Tratat de Inginerie Termica. Principiile Termodinamicii. (Treatise on Engineering Thermodynamics. The Principles of Thermodynamics)*, Editura AGIR, Bucureşti, România, 2007.

[20] Petrescu, S., Harman, C., Bejan, A., *The Carnot Cycle with External and Internal Irreversibility*, Proc. Florence World Energy Research Symposium, Energy for 21st Century: Conversion, Utilization and Environmental Quality, Firenze, Italy, 1994.

[21] Petrescu, S., Harman, C., Costea, M., Feidt, M., *Thermodynamics with Finite Speed versus Thermodynamics in Finite Time in the Optimization of Carnot Cycle*, Proc. of the 6-th ASME-JSME Thermal Engineering Joint Conference, Hawaii, USA, 2003.

[22] Petrescu, S., Petrescu, V. *Principiile Termodinamicii. Evolutie, Fundamentari, Aplicatii*, Editura Tehnica, Bucureşti, România, 1983.

[23] Stanescu, G., (Adviser: S. Petrescu), *The study of the mechanism of irreversibility generation in order to improve the performances of thermal machines and devices*, Ph. D. Thesis, U.P.B., Bucharest, 1993.

[24] Petrescu, S., Stanescu, G., Iordache, R., Dobrovicescu, A., *The First Law of Thermodynamics for Closed Systems, Considerring the Irreversibilities Generated by the Friction Piston-Cylinder, the Throttling of the Working Medium and Finite Speed of the Mechanical Interaction*, Proc. of ECOS'92, Zaragoza, Spain, Ed. A. Valero, G. Tsatsaronis, ASME, 33-39, 1992.

[25] Petrescu, S., Harman, C., *The Connection Between the First Law and Second Law of Thermodynamics for Processes with Finite Speed - A Direct Method for Approaching and*

Optimization of Irreversible Processes, Journal of The Heat Transfer Society of Japan, 33, 128, 60-67, 1994.

[26] Petrescu, S., Stanescu, G., Petrescu, V., Costea, M., *A Direct Method for Optimization of Irreversible Cycles Using a New Expression for the First Law of Thermodynamics, for Processes with Finite Speed*, Proceedings of The First International Thermal Energy Congress ITEC- 93, Marrakech, Morocco, 1993.

[27] Petrescu, S., Harman, C., Costea, M., Petre, C., Dobre, C., *Irreversible Finite Speed Thermodynamics (FST) in Simple Closed Sistems. I. Fundamental Concepts*, Revista Termotehnica, Editura. AGIR, Bucureşti, România, 1, 2010a.

[28] Petrescu, S., *The Development of Thermodynamics with Finite Speed and the Direct Method*, Tomul LVI, Fasc 3a, COFRET 2010, 5-7 mai, Iasi, Romania, 2010.

[29] Petrescu, S., Costea, M., Tirca-Dragomirescu, G., Dobre, C. *Validation of the Direct Method and its applications in the optimized design of the Thermal Machines for the increase of the Efficiency*, Conf. ASTR, Craiova, Romania, 2010.

[30] Petrescu, S., Costea, M., Harman, C., Florea, T., *Application of the Direct Method to Irreversible Stirling Cycles with Finite Speed*, Int. Journal of Energy Research, 26, 589-609, 2002.

[31] Petrescu, S., Harman, C., Costea, M., Florea, T., *A Method For Determining the Performance of Stirling Machines based on the First Law for Processes with Finite Speed and Using a PV / Px Diagram*, Proceedings Fifth World Conference on Integrated Design & Process Technology, Dallas, USA, 2000.

[32] Carvajal, I., Polupan, G., Jarquin, G., Vázquez, J., *Optimization of the Thermal Efficiency of a Robinson Engine Applying the Senft-Schmidt-Petrescu Model*, Información Tecnológica, 24, 3, 85-94, 2013.

[33] Chen, L. G., Feng, H. J., Sun, F. R., *Optimal piston speed ratio analyses for irreversible Carnot refrigerator and heat pump using finite time thermodynamics, Finite Speed Thermodynamics and Direct Method*, Int. J. of Energy Institute, 2011.

[34] Cullen, B., McGovern, J., Petrescu, S., Feidt, M., *Preliminary Modelling Results for Otto-Stirling Cycle*, Proc. ECOS - 2009, Foz de Iguasu, Parana, Brazil, 2091-2100, 2009.

[35] Feidt, M., Cullen, B., McGovern, J., Petrescu, S., *Thermodynamics Optimization of the Endoreversible Otto / Stirling Combined Cycle*, ECOS Conference, Lausane, Switzerland, 2010.

[36] Feng, H., Chen, L., Sun F., *Optimal ratio of the piston for Finite Speed irreversible Carnot Heat Engine Cycle*, Int. Journal of Sustainable Energy, 30: 6, 321-335, 2011.

[37] McGovern, J., Cullen, B., Feidt, M., Petrescu, S., *Validation of a Simulation Model for a Combined Otto and Stirling Cycle Power Plant*, Proc. of ASME 2010, 4th International Conference on Energy Sustainability, ES-2010, Phoenix, Arizona, USA, 2010.

[38] Petrescu, S., Harman, C., Costea, M., Popescu, G., Petre, C., Florea, T., *Analysis and Optimisation of Solar/Dish Stirling Engine*, Proceedings of the 31st American Solar Energy Society Annual Conference, Solar 2002, "Sunrise on the Reliable Energy Economy", Reno, Nevada, vol.CD, Editor: R. Campbell-Howe, USA, 2002.

[39] Petrescu, S., Petre, C., Costea, M., Boriaru, N., Dobrovicescu, A., Feidt, M., Harman C., *A Methodology of Computation, Design and Optimization of Solar Stirling Power Plant using Hydrogen/Oxygen Fuel Cells,* Energy, 35, 729–739. 2010c.

[40] Dobre, C., (Advisers: S. Petrescu, P. Rochelle), *Contribution to the Development of Some Methods of Irreversible Engineering Thermodynamics Applied to the Analytical and*

Experimental Study of Stirling and Quasi-Carnot Machines, Ph.D. Thesis, U. P. Bucureşti – U. Paris X, 2012.

[41] Costea, M., Petrescu, S., Harman, C., *The Effect of Irreversibility on Solar Stirling Engine Cycle Performance, Energy Conversion & Management*, 40, 1723-1731, 1999.

[42] Costea, M., Petrescu, S., Feidt, M., *Synthesis on Stirling Engine Optimization*, Thermodynamics Optimization of Complex Energy Systems, Edited by A. Bejan and E. Mamut, Kluwer Academic Publishers, USA, 403-410, 1999.

[43] Petrescu, S., *Lectures on New Sources of Energy*, Helsinki University of Technology, Otaniemi, Finland, p.320, Lectures in October 1991.

[44] Petrescu, S., Costea, M., et al., *Development of Thermodynamics with Finite Speed and Direct Method*, Editura AGIR, Bucureşti, România, 2011.

[45] Petrescu S., Feidt M., Costea M., Enache V., Petre C., Boriaru N., *Perspective d'unification de la Thermodynamique en Dimensions Physiques Finies avec la Thermodynamique à Vitesse Finie*, COFRET'14, Paris, CNAM, 2014.

[46] Petrescu, V., Petrescu, S., *A Treatment of the Concentration Overpotential Using the Thermodynamics of Irreversible Processes*, Revue Roumaine de Chimie, Romanian Academy, 16, 9, 1291-1296, 1971.

[47] Petrescu, S., *Study of the Gas - Gas Interaction with Finite Velocity for Flow Processes*, Studii si Cercetari de Energetica si Electrotehnica, Academia Romana, 23, 2, 299-312, 1973.

[48] Petrescu, S., *Experimental Study of the Gas - Piston Interaction with Finite Speed in the Case of an Open System*, Studii si Cercetari de Mecanica Aplicata, Acad. Romana, 31, 5, 1081-1086, 1974.

[49] Petrescu, V., (Adviser: S. Sternberg), *Electrode Processes and Transport Phenomenon at the interface of Chlorine-Carbon Electrode-Molten Salt*, PhD Thesis, I. P. Bucureşti, 1974.

[50] Petrescu, S., Petrescu, V., Stanescu, G., Costea, M., *A Comparison between Optimization of Thermal Machines and Fuel Cells based on New Expression of the First Law of Thermodynamics for Processes with Finite Speed*, Proc. First International Thermal Energy Congress, ITEC - 93, Marrakech, Morocco, 1993.

[51] Petrescu, S., Zaiser, J., Harman, C., Petrescu, V., Costea, M., Florea, T., Petre, C., Florea, T.V., Florea, E., *Advanced Energy Conversion - Vol II,* Bucknell University, Lewisburg, PA, USA, 2006a.

[52] Enache V., Petrescu S., *Algoritm local pentru optimizarea costului reţelelor arborescente de conducte*, Proceedings of the VIIth Edition of the Int. Conf. ACADEMIC DAYS of The Academy of Technical Science in Romania, Bucharest, pp. 236, Editura AGIR, Bucureşti, România, 2012.

[53] Enache, V., Petrescu S., *Optimizarea costului instalaţiilor arborescente de transport*, Rev. Termotehnica, XVI, 2/2012, p. 4, Ed. AGIR, Bucureşti, 2012.

[54] Enache, V., Petrescu, S., Bolohan, R., *Condiţii de optim în sistemul Cardio-Vascular-Pulmonar obţinute în cadrul Termodinamicii Ireversibsile cu Viteză Finită, I. Debitul de oxigen în funcţie de viteza sângelui*, Rev. Chim., Bucureşti, 2105 (in press).

[55] Enache, V., Petrescu, S., Bolohan, R., *Condiţii de optim în sistemul Cardio-Vascular-Pulmonar obţinute în cadrul Termodinamicii Ireversibile cu Viteză Finită. II. Optimizarea puterii utile furnizate de organism*, Rev. Chim., 2015 (in press).

[56] Petrescu, S., Enache, V., *Applying the Finite Speed Thermodynamics (FST) to the Human Cardiovascular System*, National Conf. of Thermodynamics. (NACOT), Constanta, 2013.

[57] Petrescu, S., Costea, M., Timofan, L., Petrescu, V., *Means for qualitative and quantitative description of the Cardio-Pulmonary System Operation within Irreversible Thermodynamics with Finite Speed*, ASTR Conference, Sibiu, 2014.

[58] Petrescu, S., Petrescu, V., Costea M., Timofan, L., Danes, S., Botez, G., *Discovery of Quantum Numbers In the Cardio-Pulmonary Interaction studied In Thermodynamics with Finite Speed*, Conf. ASTR, Sibiu, Romania, 2014.

[59] Petrescu, S., Harman, C., *The Jump of an Electron in a Hydrogen Atom using a Semi-classical Model*, Rev Chim., Bucharest, English Edition, 2, 1-2, 3-10, 2001.