MEANS FOR QUALITATIVE AND QUANTITATIVE DESCRIPTION OF THE CARDIO-PULMONARY SYSTEM OPERATION WITHIN IRREVERSIBLE THERMODYNAMICS WITH FINITE SPEED

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Abstract: Illness and aging are irreversible processes, which inevitably affects us all. The answers to the questions how, why, and how much irreversible are the cardio-respiratory system processes, will allow improved design of artificial hearts and lungs (vital “spare parts"), and health care before passing various pathological "thresholds of irreversibility" that generate diseases and premature aging. Onsager (1930) and then Prigogine (Nobel Price laureates) have shown that biological processes comply with Second Law of Thermodynamics (Entropy existence and growth), not only with First Law (transformation and conservation of energy), which was already accepted in Physiology and Biology. They created Linear Phenomenological Irreversible Thermodynamics (LPIT) that, so far, is the basis of irreversibility research in Biology and Physiology, but has not been substantially applied in the field of Thermal Machines. The Thermodynamics with Finite Speed (TFS), this new branch of Irreversible Engineering Thermodynamics used the LPIT of Onsager and Prigogine in its mathematical approach. Thus, it contains "the core of its essential and fundamental", but, in addition, it is adapted and developed to describe the irreversible processes in any thermal machines. Our belief that biological systems (people, animals, birds, fish) are a kind of natural thermal machines (not invented and built by engineers), allowed us to hope that TFS can provide tools for a qualitatively and quantitatively description of these systems or parts of them. A very important part is the cardio-respiratory system. This paper deals with the heart-lung interaction in the frame of TFS, aiming to generate means of qualitative and quantitative description of the oscillating processes taking place inside. The main average momentary parameters are introduced to describe these processes, adapted to this new domain. The purpose of the analysis is to establish a "Thermodynamic Scheme of Operation" of these subsystems in interaction, together with a new diagram so called PV/Px diagram for the description of irreversible processes in Pulmonary Cardiovascular System.
Keywords: Cardio-Pulmonary System, Artificial Heart, Direct Method, Thermodynamics with Finite Speed, Stirling Machines Performances, Heart Efficiency and Power, PV/Px Diagram for Heart.

1. INTRODUCTION

Mechanical Engineering has got important progresses in designing and producing artificial hearts and artificial lungs in the last years. With a better understanding of the processes in the Cardio-Pulmonary system these new artificial organs can be improved in their Performances of Efficiency, Power and Endurance, in a similar way it happens in the domain of Thermal Machines. With the help of the novel PV/Px diagram for Stirling Machines and the Direct Method from Thermodynamics with Finite Speed we were able to recently develop a Scheme of Computation of the Performances (Efficiency and Power) for 12 Stirling Engines (with the highest performances in the world) and 16 regimes of their functioning, [1] and for 4 Solar Stirling Engines. [2-5].

The Cardio-Respiratory System works in millions of men and women every day and night in more than 16 regimes of functioning. Understanding “how this is happening” and how we can describe qualitatively and quantitatively this “miracle” is essential in the progress of Bio-engineering, in this domain of design and building of artificial organs. We believe that Thermodynamics with Finite Speed (TFS) [6- 22] and the Direct Method (DM) [8, 9] also can help in this domain of research, as it helped in the case of very complicated Machines like Stirling Machines [1-5, 14-22]. Thus, we “took the courage” and developed a *Novel Scheme of Computation for Cardio-Pulmonary System based on a novel PV/Px Diagram* which explains in details how this Complex System works, which we present in this paper.

In this interdisciplinary Research (Mechanical Engineering, Thermodynamics, Physical Chemistry, Electrochemistry, Electro-Physiology, Biology) we have followed, from the epistemological point of view, the advices of two great scientists:

(a) Einstein: "*The most practical thing is a good theory*".

(b) Thomson Kelvin: **"***In order to understand anything you need to develop a mechanical model*".

Following these two advises we have developed a new branch of irreversible Thermodynamics, which L. Stoicescu and S. Petrescu [23-29] called it from the very beginning (1964): *Thermodynamics with Finite Speed* (TFS) [8].

We used the Direct Method (DM) [8, 9] "invented" in framework of TFS in order to study and optimize many cycles of Thermal Machines [1-29]. We extended the utilization of this Method (DM) from TFS also for Electrochemical Devices [38-42].

Developing this new branch of Irreversible Thermodynamics (TFS) and the Direct Method (DM) for Study and Optimization of Thermal Machines and Electrochemical Devices we did hope to get "a good Theory" (as Einstein's "advised us") capable to be used in a "practical work" of Mechanical Engineers and Chemical Engineers namely: Design for improvement of Performances (Efficiency / COP and Power Production/Consumption) of Thermal Machines and Electrochemical Devices.

The "greatest" achievement of TFS and DM we have obtained [1, 6, 7, 18-22] was the Development of a Scheme of Computation of Performances (Efficiency and Power) which was Validated successfully for 12 Stirling Engines (with the best performances in the world) working in 16 regimes of operation, and also for 4 (the best in the world) Solar Stirling Engines [2-5]. Also the utilization of TFS and DM for optimization of SEHE Systems (Solar Stirling+Hydrogen Production in Electrolyzers→H_2 Storage—Fuel Cell Electricity production) [3, 21] was another important success of this new Branch of Irreversible Thermodynamics (TFS).

These successes of TFS and DM were not possible until we have developed "a Mechanical Model for Understanding how Stirling Machines works", [1, 6, 7, 18-22], as Thomson Kelvin has "advised us" (b).

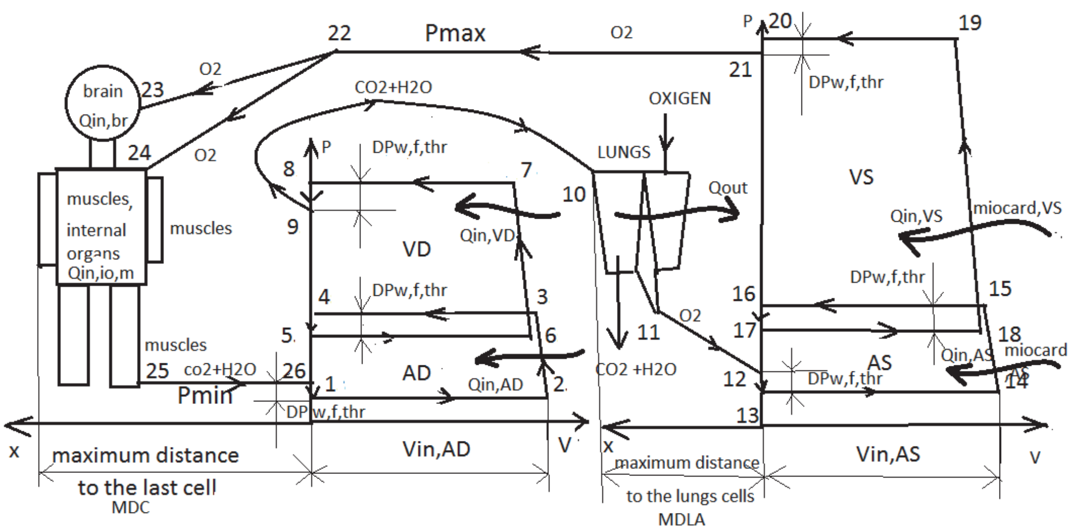

Fig. 1. A novel PV/Px Diagram for explaining and computing the Performances (Efficiency and Power) of Cardio-Pulmonary System using the Direct Method from Thermodynamics with Finite Speed.

Meanwhile Thermodynamics with Finite Time (TFT) was criticized by Moran [35, 36] and Gyftopoulos [37]. The Moran's papers are entitled: "*A Critique of Finite Time Thermodynamics***"** [35]**,** and "*On Second Law Analysis and the failed Promises of Finite Time Thermodynamics*" [36]**.** Because of these critics, more and more researchers started to use and develop TFS **(**from China: L. Chen and his team [12, 13], from Ireland and France [15-17], from Mexico [14]) with substantial advantages, by taking into account also internal irreversibilities, which TFT could not do**.**

Based on these achievement of TFS [1-34] our interdisciplinary team "took the courage and attacks" in this paper the problem of developing a "Thermodynamic Irreversible Model" in the framework of Thermodynamics with Finite Speed [6-9], in order to use it for completely analytical computing (as was done for all cycles previously studied [8]), based on DM [9], *analytical formulas* *for Efficiency and Power of the Heart*. Such formulas, after Validation (as has been done for example for Stirling Engines [1-8, 20]), could be used by Mechanical Engineers, in cooperation with Chemical Engineers, Bio-Engineers, and Medical Doctors for better Design of artificial Hearts and afterwards also for artificial Lungs, which works (as it is very well known) in a "strong correlation". This correlation has been already obtained by us in a previous paper [11], in which we have *discovered a quantized formula for the interaction between heart and lungs*, seen as a *pump* for blood (the heart) and as a *volumetric compressor* with air (the lungs).

Using this formula [11]:

$$\boldsymbol{F_i = F_p \cdot (2 + N/4)} \quad (1)$$

where: $\boldsymbol{N = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, \ldots}$

and the *PV/Px Diagram* form the Figure 1, we can now use the Direct Method from TFS [6-9], in order to express the Power and the Efficiency of the Heart, Lungs, and the total Power of Cardio-Respiratory System.

2. REGIMES OF FUNCTIONING OF THE CARDIO-RESPIRATORY SYSTEM, AND COMPUTATION OF ITS POWER USING THERMODYNAMICS WITH FINITE SPEED AND THE DIRECT METHOD

In Figure 2, we show the Stationary States and "quantum jump Processes" between these stationary States, measured for one person (SP) in 7 days, at different hours in the day. For one day, Table 1 shows these measurements data.

Table 1. **Heart and Lung Frequencies relative to position and time of the day (October 18, 014) for SP**

State	Hour	Fi	Fp	Rf=Fi/Fp	Position
0	6:00	66	22	3.00	in bed, wake up
1	9:35	103	25.5	4.04	after breakfast and physical activity
2	9:42	90	24	3.75	in bed, light activity
3	9:51	117	25	4.68	in bed, moving the leg
4	10:03	80	24	3.33	in bed, after sigh
5	10:14	82	26	3.15	in bed
6	10:38	91	26	3.50	
7	10:59	83	25.5	3.25	
8	13:45	84	28	3.00	after walk
9	14:02	91	28	3.25	after carrying bags
10	16:00	77	25.5	3.02	in bed, after the nap
11	16:14	79	22.5	3.51	in bed, light activity
12	17:00	71	24	2.96	
13	17:40	69	19.5	3.54	in bed
14	17:45	76	18	4.22	in bed, after slight movement
15	17:57	70	23	3.04	in bed, sitting
16	18:10	78	28	2.79	standing
17	20:30	87	25	3.48	on chair, working to the computer
18	23:02	60	24	2.50	on chair, working to the computer
19	23:05	56	24.5	2.29	on chair, working to the computer
20	23:12	62	22.5	2.76	on chair, working to the computer
21	23:26	60	20	3.00	in bed, horizontal position
22	23:33	63	21	3.00	in bed, horizontal position

Based on Figure 2, we can get the "distribution of the Stationary States" for different "quantum levels" characterized by the *quantum number N* that enters in the equation (1) which correlates the two speeds (frequency) of the subsystems: heart, with F_i and lungs, with F_p.

In Figure 3 we show this distribution for a person (SP), which actually represents a sort of *personal Characteristic of the Heart-Lungs interaction.*

Having this *personal Characteristic it is possible to specify the main parameters of a person* for which a certain *personalized artificial Heart can be chosen from a set of available hearts. Before the implant the Doctor has to choose that proper artificial heart, which suits the best for that person* [43-44]. *This particular heart must be capable to cover all regimes of functioning illustrated in the Diagram from* Figure 2, for that person.

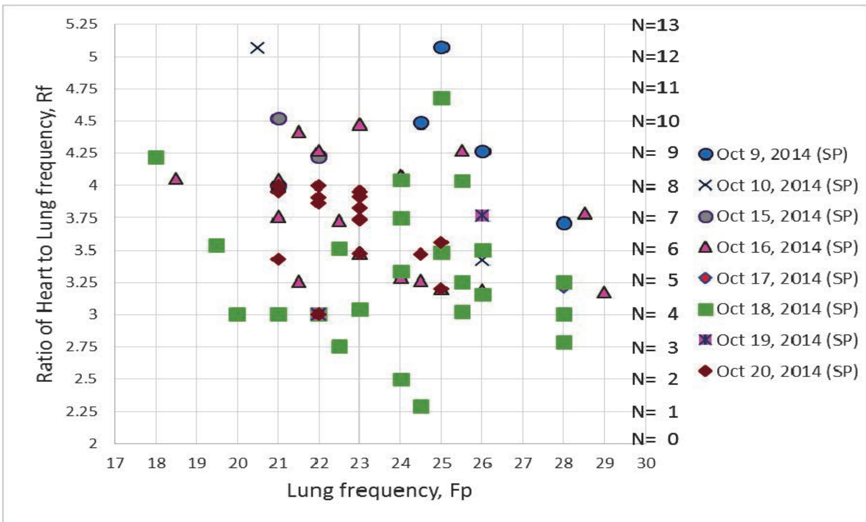

Fig. 2. Stationary States and corresponding quantum levels, measured for one person (SP) in 7 days.

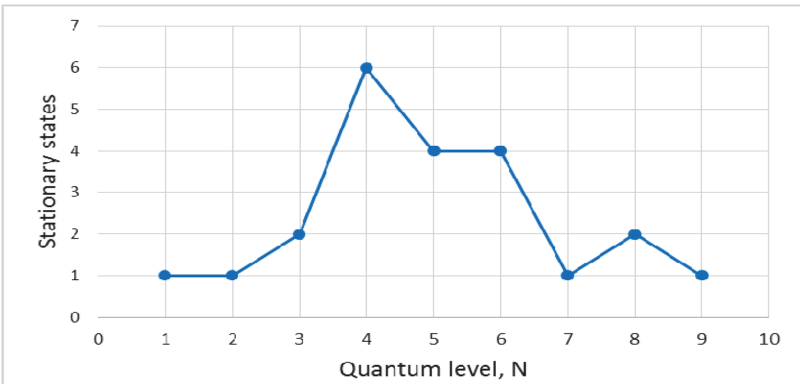

Fig. 3. Distribution of the Stationary States for different quantum levels in a common day, for SP.

Using Figure 1, data from Figure 2 and 3, and the Direct Method from TFS [6-9, 45-55], the following Parameters can be estimated:

a. The value of *N* for the *fundamental regime* (point 0 in Fig. 2), immediately after wake up every morning of the particular person. For example, for SP we get this number *No*=4, which correspond to a value of F_i/F_p = 66/22 = 3.

b. The most probable quantum level = the value of the number N_{mp}=4, corresponding to $R_{f,\,mp}$ *=3.*

*For another person (S.D.)** we build Figure 4. One can see that the *most probable* $R_{f,\,mp}$ *=6 for which the most probable quantum number level is* N_{mp}*=16 (for SD).* This is an *experimental proof that each person has its own number* N_{mp}.

Based on data illustrated in Figure 4 it results $R_{f,\,min}$ = 5 with 3 appearances; $R_{f,\,max}$ = 7.5 with 3 appearances as well, and $R_{f,\,mp}$ (most likely) = 6 with 14 appearances. According to equation (1), three characteristic quantum numbers can be derived: N_{min} = 12, N_{max} = 22, and N_{mp} = 16 for SD. With these values we can calculate the three characteristic Power consumption of cardio-respiratory system of SD: P_{min}, P_{max}, and P_{mp} (most likely). These values can be used to "custom design" of the artificial heart and lungs for a SD, as potential patient, in case of occurrence of a transplant need.

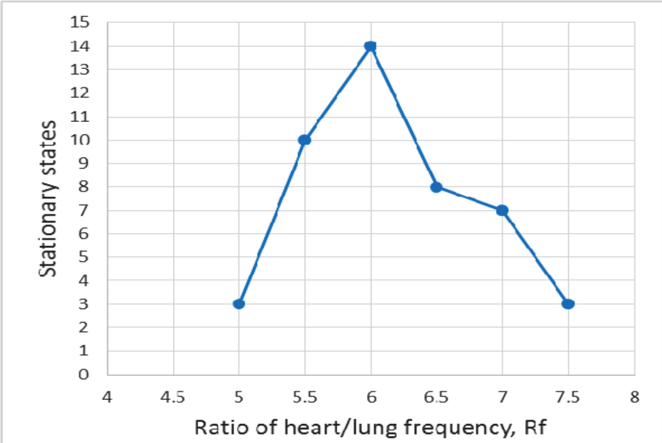

Fig. 4. Frequency Ratio $R_f=F_i/F_p$ distribution of the 45 stationary states, during a common day for SD.*

c.Computation of the Power in the Heart-Lung System in the two regimes: *fundamental stationary state* , and the *most probable stationary state:*

$$P_{total} = P_{heart}+P_{lungs}$$

$$P_{total} = F_i\,.\sum\Delta P_i\,.\Delta V_i + F_p\,.\Delta P_p.\Delta V_p = F_i\,.[\,\sum\Delta P_i\,.\Delta V_i+\Delta P_p\,.\Delta V_p/(2+4/N)]$$

where:

$$\sum\Delta P_i.\Delta V_i = [(P_9-P_{26})+3.\Delta P_{w,f,thr}\,].V_{in,AD} + [(P_{21}-P_{12})+3.\Delta P_{w,f,thr}\,].V_{in,AS}$$

$\Delta P_{w,f,thr}$ is expressed from TFS [6-9, 37] corresponding to the First Law for Processes with Finite Speed:

$$dU = \delta Q - P_{mi}\,[1 +/- aw/c +/- \Delta P_f/P_{mi} +/- \Delta P_{thr}/P_{mi}\,].dV$$

$$\Delta P_{w,f,thr} = P_{mi}\,.[\,aw/c + \Delta P_f/P_{mi} + \Delta P_{thr}/P_{mi}\,].$$

$$\Delta P_f = A + B.\,F_i \quad ; \quad \Delta P_{thr} = C.\,F_i^{\,2} \;;$$

with A, B and C - coefficients which have to be validated based on comparison with experimental data.

With all these data *a proper artificial heart could be chosen for a person (i.e., SP).* For another person (S.D), another *heart* must be chosen in order to *suit to her cardio-respiratory system operation.*

3. CONCLUSIONS AND PERSPECTIVES

Our belief that biological systems (people, animals, birds, fish) are a kind of "*natural thermal machines",* allowed us to use Thermodynamics with Finite Speed (TFS) [1-10] in order to provide tools for a qualitatively and quantitatively description of these systems or parts of them. One of "the most important part" of them is the *Cardio-Respiratory System*.

Extending the application of TFS to this Biological System, we introduced the *main average momentary parameters* capable/useful *to describe these Oscillating Biological Processes, adapted to this new domain***.** Using the similarity with thermal machines (pump/heart and compressor/lungs) we have "invented" a *"Thermodynamic Scheme of Operation" of these subsystems in interaction, together with a new Diagram so called PV/Px diagram for the description of irreversible processes in Pulmonary Cardiovascular System***.**

Using this new Diagram PV/Px, the new concepts from TFS and the discovery of quantum correlation between F_i and F_p (Eq. 1) [11], the total Power P_{total} has been computed as an analytical quantized expression. The fundamental parameters of any person can be now determined experimentally for *"the main/characteristic Regimes" of Functioning as N_o, N_{mp}, N_{min}, N_{max}, and with*

* The authors of this paper want to express many thanks and their appreciation to Prof. PhD. chem. Silvia Danes (S.D), for her enthusiasm and very many experiments/measurements she did on herself, obtaining extremely important data, based on which the Figure 4 has been build.

these the characteristic Powers could be determined: *Minimum Power*, *Fundamental Stationary Regime (when sleeping) Power*, the most Probable Regime Power, the *Maximum allowable* (without danger of “too high irreversibilities”=illnesses like: stroke or hard attack) *Power* could be now computed for any person. These *personalized data* will become *the main parameters for design of personalized artificial hearts*, we hope. In this way Mechanical Engineers will help physiologist and medical doctors to design and build artificial hearts for any person taking into account : age, sex, height, weight for any person which will need an artificial heart, or/and an artificial lung.

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MIJLOACE DE DESCRIERE CALITATIVĂ ŞI CANTITATIVĂ A FUNCŢIONĂRII SISTEMULUI CARDIO-PULMONAR ÎN CADRUL TERMODINAMICII IREVERSIBILE CU VITEZĂ FINITĂ

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Rezumat: Îmbolnavirea şi îmbătrânirea sunt procese ireversibile care, inevitabil, ne afectează pe toţi. Răspunsurile la întrebările cum, de ce, şi cât de ireversibile sunt procesele din sistemul Cardio-Respirator, vor permite proiectarea îmbunătăţită a inimilor şi plamânilor artificiali. Onsager (1930) şi apoi Prigogine (laureati Nobel) au arătat că procesele biologice respectă Principiul II al Termodinamicii (existenţa şi cresterea Entropiei), nu numai Principiul I (transformarea şi conservarea Energiei), care era deja acceptat in Fiziologie şi Biologie. Ei au creat Termodinamica Ireversibilă Fenomenologică Liniară (TIFL) care, pâna în prezent, este baza cercetărilor de ireversibilitate din Biologie şi Fiziologie, dar care nu s-a aplicat substanţial şi în domeniul Maşinilor Termice. Apariţia Termodinamicii cu Viteza Finită (TVF), această nouă ramură a Termodinamicii Ireversibile, a făcut apel la TFIL a lui Onsager şi Prigogine, deci conţine “sâmburele esenţial şi fundamental al acesteia”, dar, în plus, este adaptată şi dezvoltată pentru a putea descrie procesele ireversibile din Maşinile Termice de orice fel. Convingerea noastră că şi Sistemele Biologice (oameni, animale, păsări, peşti) sunt un fel de Maşini Termice Naturale, ne-a permis să sperăm ca TVF poate descrie şi aceste sisteme sau părţi din ele. O importantă parte din acestea este Sistemul Cardio-Respirator. Lucrarea de faţă abordează interacţiunea inimă-plămâni în cadrul TVF, dorind să genereze mijloacele de descriere calitativă şi cantitativă a acestor procese oscilante. Sunt introduşi principalii parametri medii momentani pentru descrierea acestor procese, adaptaţi acestui nou domeniu de aplicare. Scopul analizei constă în elaborarea unei “Scheme Termodinamice de Funcţionare” a acestor subsisteme în interacţiune, împreună cu o nouă diagramă numită Diagrama PV/Px pentru descrierea proceselor ireversibile din Sistemul Cardiovascular-Pulmonar.