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WHAT IS QUANTUM BIOLOGICAL THERMODYNAMICS WITH FINITE SPEED OF THE CARDIO-PULMONARY SYSTEM: A DISCOVERY OR AN INVENTION?

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Abstract. The successful development, applications and validation of Thermodynamics with Finite Speed (TFS) for Thermal Machines (TM) has prompted us to try to extend it to Biological Systems. As the most important Validation of TFS was achieved for Stirling Machines where basically two pistons are in continuous motion, the Cardio-Pulmonary System appeared as an appropriate candidate for study. It can be seen as an ensemble of two biological machines: a *liquid pump with valves* (the Heart) and *an air compressor* (the Lung), similarly to a two pistons machine (as in Stirling one). This association allowed us to invent a new pV/px diagram for this Biological System, similar to the one previously introduced for Stirling Machines. By using these new concepts and tools, experimental studies on more than 50 peoples (children, yang, adults, old) were done. Thousands of *stationary states* and *processes with and without quantum jump* (new concept) in the Cardio-Pulmonary System were analyzed and 5 new diagrams were invented, where *this system can now be described qualitatively and quantitatively* in similar way to the TFS approach. Thus, the *equations of the 4 fundamental processes in the Cardio-Pulmonary System* were discovered, creating what we call *Quantum Biological Thermodynamics with Finite Speed*, as an extension of TFS from Thermal Machines to one of the most important Biological System in humans and animals.

Key words: Thermodynamics with Finite Speed, Quantum Biological Thermodynamics with Finite Speed, Stationary States in Cardio-Pulmonary System, Processes with Quantum Jump in Cardio-Pulmonary System.

1. INTRODUCTION

The wide range of domains where the Constructal Theory of Prof. Adrian Bejan applies [1-4] encouraged us to try to extend the Thermodynamics with Finite Speed (TFS) to Biological and Social Systems [5–11]. Like in Bejan's Constructal Theory [1–4], we do consider that the *speed of any process* is a very important parameter in Thermodynamics with Finite Speed, applied to any kind of process, either in Thermal Machines [12–15], Electrochemical Apparatus [11, 15–17], Biological Systems [5, 6, 8–11], or in Society Processes [7].

From all biological systems, our attention focused on the Cardio-Pulmonary System which is extremely important for sustaining life of animals and human beings. The Heart is just a "naturally designed" liquid (blood) pump, and the Lungs are just similar "naturally designed" air compressors. Certainly, like in the Constructal Theory vision, the Nature designed and optimized these Biological Machines, as mechanical engineers also do in their job, namely a continuous Optimization of Thermal Machines (engines, compressors, pumps etc.). Seeking for Thermal Machines having some similarities with the Cardio-

Pulmonary System, we discovered that Stirling Machines and Cardio-Respiratory Systems *have something in common*, namely, both have "two pistons", working together in a certain "*ordered interaction*". For Stirling Machines, we have already developed a very successful Computation Scheme of Performances (Efficiency and Power) by using Thermodynamics with Finite Speed and the Direct Method [12–15] that was validated for 15 Stirling Machines. This success of TFS made us confident in its extension also to Cardio-Pulmonary System study.

The present paper presents the main achievements of this extension in terms of a new diagram *pV/px* for heart and lung operation, the new specific processes in Cardio-Pulmonary System and the equations describing them, and the five diagrams for the study of *stationary states* and *processes with and without quantum jump* that have been introduced in what we called *Quantum Biological Thermodynamics with Finite Speed (QBTFS).*

2. THE pV/pX DIAGRAM FOR CARDIO-RESPIRATORY SYSTEM

The new diagram introduced for Stirling machines and called "*pV/px*" [15, 18] was adapted for Cardio-Pulmonary System. Presented for the first time in [5, 11], this diagram helped us to extend the concepts and the Direct Method from Thermal Machines to an extremely important Biological System, namely the Cardio-Pulmonary System. Figure 1 shows the Heart operation as a *liquid pump* having actually "two corps" (working simultaneously), each of them having two stages (atriums and ventricles). As in TFS, the diagrams contain the losses in the valves, that are responsible of very important "irreversibility losses", especially in many illnesses (atrial/ventricular fibrillation, fluttering etc.).

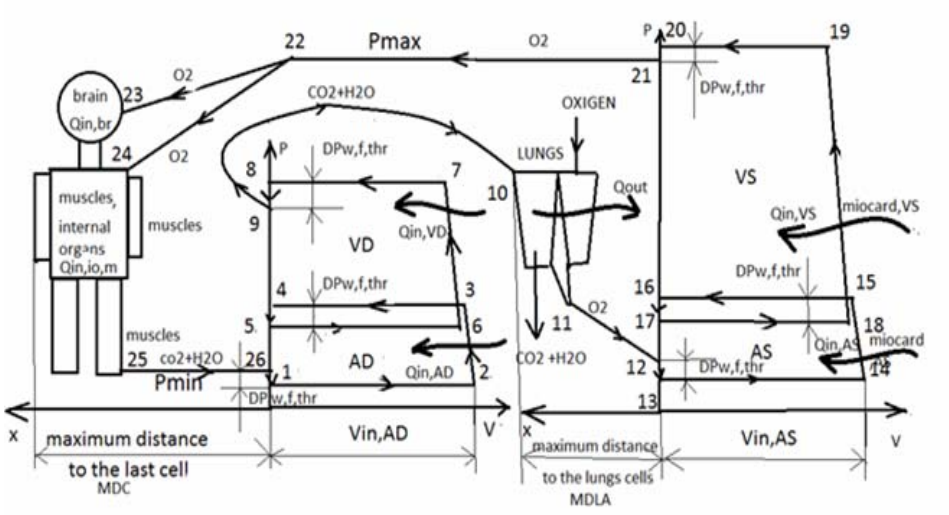

Fig. 1 – The *pV/px* Diagram for Cardio-Pulmonary System [5, 11].

This diagram (Fig. 1) is essential for the computation of *Irreversible Work per Cycle* of each Biological Machine (Heart and Lungs), *Power* consumed by each, (and together), of *Entropy Source* for each (and together). Also, it helps to analyze the normal and the abnormal (in the case of illness) functioning of Heart and Lungs based on 5 diagrams invented by us using equation (1) and the new concepts that we have introduced [8, 11], namely *Stationary States* in Cardio-Respiratory System, and *Processes (simple or complex) between successive Stationary States.*

3. EQUATIONS FOR CARDIO-RESPIRATORY SYSTEM PROCESSES

Based on experiments analysis we have done on thousands measurements of Heart (F_H) and Lung (F_L) *Frequencies* in *Stationary States* on different persons and after plotting the diagram $F_H = f(F_L)$ [6], we discovered *a very simple equation* correlating these two *oscillation frequencies:*

$$F_H = F_L\left(2+\frac{N}{4}\right), \tag{1}$$

where N is an integer number that we called *quantum number of the interaction between the Heart and Lung in a stationary state*, in a healthy person. We believe that if a person does not achieve easy and quite fast (1-2 minutes) such a state, Eq. (1) is not validated for she or he, which means this person may have already illness or will have it in the future.

The two previously mentioned frequencies **(**F_H or/and F_L**)** may be constant (for minutes, tens of minutes or even hours) in what we called *stationary quantum states* (SQS), associated to different positions (laying, sitting on a chair, walking, or doing repetitive physical work, etc).

By connecting two *successive stationary states* we have got a *process line* similar with the lines illustrating Reversible Processes in Classical Thermodynamics (CT) diagrams, such as *p-V*, *T-S*, *h-s* etc., generally used in Thermal Machines study and design.

Equation (1) applied to the *successive quantum stationary states* 1 and 2, representing the initial and final states of a quantum process, can be written as:

$$F_{H,1} = F_{L,1}\left(2+\frac{N_1}{4}\right), \quad F_{H,2} = F_{L,2}\left(2+\frac{N_2}{4}\right). \tag{2)-(3}$$

As in CT, three equations of the human Cardio-Pulmonary System will result from Eqs. (2) and (3), when a *state parameter* is kept constant during each corresponding process:

$$\frac{F_{L,2}}{F_{L,1}} = \frac{8+N_1}{8+N_2}, \quad \text{at } F_H = \text{constant}, \qquad \text{Iso-Pulse process} \tag{4}$$

$$\frac{F_{H,2}}{F_{H,1}} = \frac{8+N_2}{8+N_1}, \quad \text{at } F_L = \text{constant}, \qquad \text{Iso-Rhythm process} \tag{5}$$

$$\frac{F_{H,2}}{F_{H,1}} = \frac{F_{L,2}}{F_{L,1}}, \qquad \text{at } N = \text{constant}, \qquad \text{Iso-Quantum process.} \tag{6}$$

The general process corresponding to the polytropic one in Classical Thermodynamics is introduced by the *polytropic coefficient* given by the slope of the process line:

$$\mu = \frac{\Delta N}{\Delta F_L}. \tag{7}$$

By discovering with experimental measurements of F_H and F_L the connection between the *slope of polytropic process* and *change of position* or other *processes generated by activities* (eating, walking, running, climbing), one can express the polytropic equation as:

$$F_{H,2} = F_{L,2}\cdot\left(2+\frac{N_1}{4}+\mu\frac{F_{L,2}-F_{L,1}}{4}\right). \tag{8}$$

Processes governed by the above equations are illustrated in Figs. 2–4.

4. THE FIVE DIAGRAMS FOR STUDY OF THE STATIONARY STATES AND PROCESSES WITH AND WITHOUT "QUANTUM JUMP" IN THE CARDIO-PULMONARY SYSTEM

We invented 4 diagrams inspired from Classical Reversible Thermodynamics similarly to *p-V*, *T-V* ones, where we replaced the 3 parameters of equilibrium state: *p*, *V*, *T*, by other 3 parameters of State corresponding to Cardio-Pulmonary Systems, namely: F_H *– frequency of Heart* (rhythm of Heart oscillations), F_L *– frequency of Lung* (rhythm of Lungs oscillations), and N *– quantum number* which

characterizes the *interactional order* between the *two pistons* of *biological machines*. As it is very well known by mechanical engineers and also designers of Stirling Machines, these machines would not work efficiently (with highest efficiency or COP) if between the motions of the two pistons would not be a *difference in phase* of 90°. We have discovered experimentally on more than 50 people (children, young, adults, old people, men and women) that in a similar way the Cardio-Pulmonary System works normally (healthy) only if a *certain order in the interaction between its two pistons* exists, quantified by equation (1), where the number *N* expresses actually *the difference in phase* between the oscillatory motion of these two pistons. We explained previously [10] why the ration R_f is actually quantified with the number *N*, which differs from a *stationary state* to another, and from person to person, in different moments during the *circadian cycle*. We have elaborated several experimental protocols for determining the diagrams that are characteristic for any person.

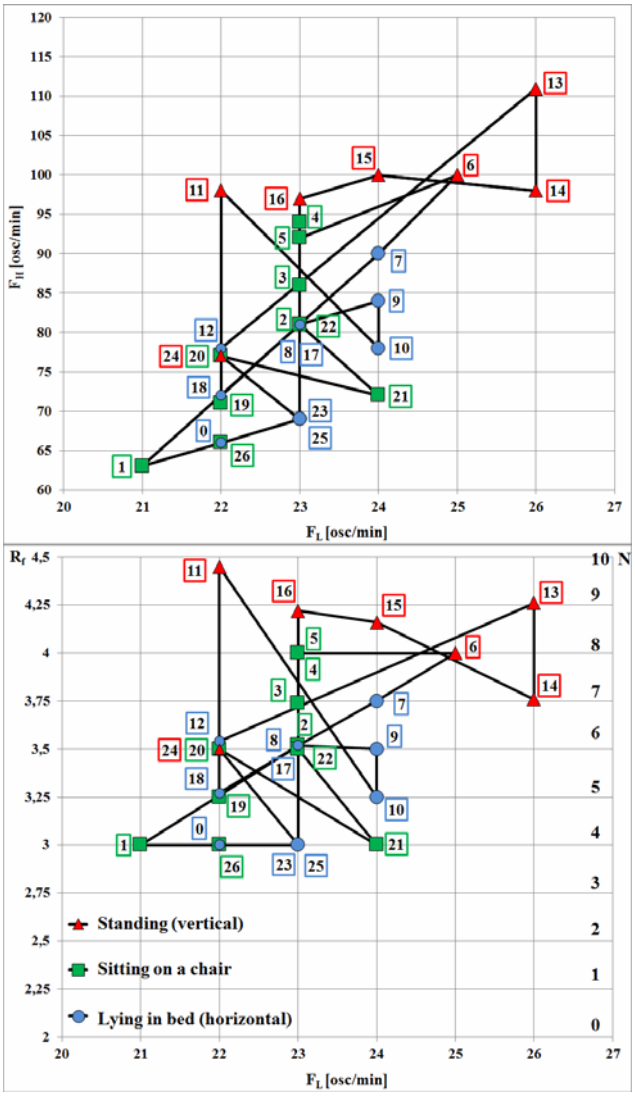

Fig. 2 – Diagrams $F_H = f(F_L)$ and R_f, $N = f(F_L)$.

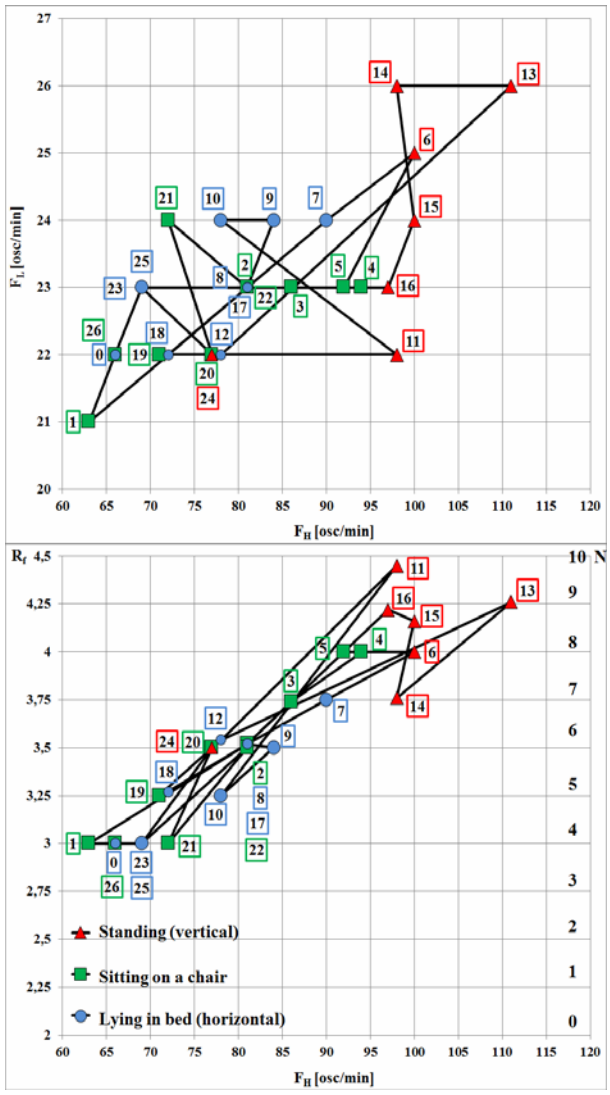

Fig. 3 – Diagrams $F_L = f(F_H)$ and R_f, $N = f(F_H)$.

In Figs. 2 and 3 we present 4 of these diagrams for a man (SP) aged 77 years, in order to illustrate how the processes in a day and night can be represented in a similar way like in Classical Thermodynamics (CT) for thermal machines. From these diagrams we can obtain very important information about how the Heart and Lungs from Cardio-Pulmonary System work in their *very well organized interaction*, in healthy persons, and *how bad organized* they work in not very healthy persons (or ill persons). The *main sign of a healthy person* (seen in such diagrams) is the fact that all or almost all states are *stationary states*, placed on a certain quantum number *N*, in the diagrams from Figs. 2, 3 and 4. When *a process determined by a change of posture* appears, we will see in all of these diagrams a *process (a line connecting the two states: initial and*

final) with or without a *quantum jump, corresponding to a change of, or a constant N.* A constant *N* process (*iso-quantum number*) corresponds to equation (6) and is represented by processes 0–1, 8–9, 5–6.
We also see processes described by equation (5) with constant F_L (processes 11–12, 16–17, 9–10, 2–3, 4–4, 13–14). There are also processes with constant or quasi-constant F_H (process 14–15, eq. (4)).

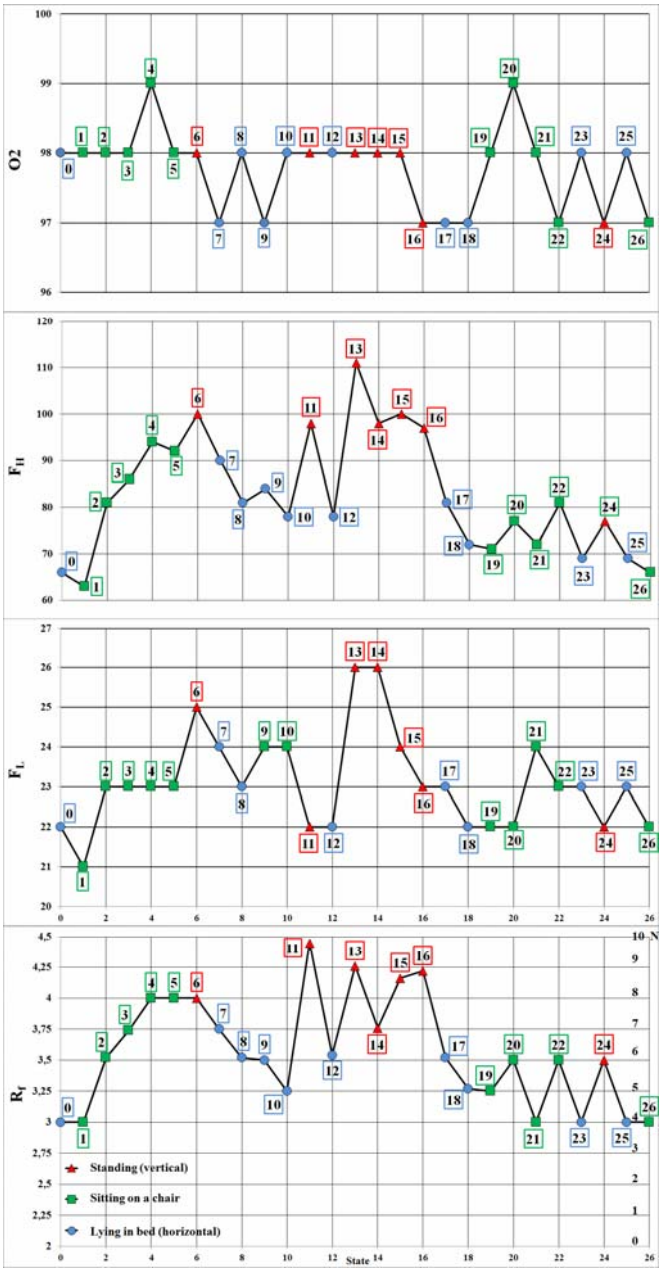

Fig. 4 – Diagrams $O_2 = f$(Number of the state); $F_H = f$(Number of the state); $F_L = f$(Number of the state) and R_f, $N = f$(Number of the state).

The stationary states corresponding to the horizontal position and sitting on the chair are usually in the bottom and medium domain of all diagrams (circles and quadrates points), but standing on the feet and walking positions correspond (triangles) to the upper side domain of the diagrams. This is caused by the increase of F_H, because more Oxygen is needed for more effort consumed in the muscles. Also when eating (for example the breakfast, process 1–2), the *stationary state* is changed, with increasing the quantum number *N* (*quantum jump up* from 4 to 6), because of the effort of the muscles during eating, and the beginning of the metabolism process involving the muscles of the stomach.

If the position changes appear, from standing to siting or laying in the bed, the state (point on diagram) is moving usually to lower quantum number with a *quantum jump down* (process 16–17 where *N* changes from 9 to 6, and process 11–12 where *N* goes from 10 to 6).

In the opposite situation, changing the position from horizontal (in bed) to vertical (on the feet), the quantum number *N* is increasing with a *quantum jump up* (process 12–13 where *N* is increasing from 6 to 9, and process 10–11, where *N* is increasing from 5 to 10).

In the fifth diagram presented in Fig. 4 we see the correlations between the change of Oxygen percent in the blood O_2, the change of frequency of the heart F_H, the change of the frequency of the lung F_L and the change in the Frequency ratio $R_f = F_H/F_L$ (corresponding also to the change of the quantum number *N*) over a day in which different activities were carried out. There are very obvious correlations between the changing of the 4 parameters of state: O_2, F_H, F_L, R_f (respectively *N*).

The main correlation is based on the *discovered formula* (Eq. 1) which led us to express quantitatively "the very well organized" interaction between Heart and Lung.

Based on these diagrams combined with the diagram from Fig. 1, and using the Direct Method from TFS we can compute now the *Power*, *Entropy Source* and *Efficiency* of this wonderful and extremely efficient Biological Machines that compose the Cardio-Pulmonary Systems in humans and animals.

5. CONCLUSIONS AND PERSPECTIVES

The answer to the title question is that *Quantum Biological Thermodynamics with Finite Speed of Cardio-Pulmonary System* (QBTFSCPS) is both *a discovery based on Equation* (1) and also *an invention based on the 5 diagrams*, built in a similar way to those from Classical Thermodynamics, but using new fundamental concepts such as stationary quantum states, processes between stationary quantum states, with or without quantum jump.

This discovery is in agreement with the Bejan's Constructal Law in the sense that "the natural Process which designed human being has Optimized the functioning of this essential System, the Cardio - Pulmonary System" (in healthy people). Unfortunately, in not very healthy people the interaction is not any better organized and the consequences could be dramatically.

This new branch of Irreversible Thermodynamics, called *Quantum Biological Thermodynamics with Finite Speed* that we applied here to Cardio-Pulmonary System can help the designer teams of Doctors, Physiologists, Mechanical Engineers, Electronic and Electrical Engineers, Chemist and Electrochemist, to design Optimized and Personalized Artificial Hearts that will suit better for different types of patients in the near future.

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