APPLICATION OF ENERGY-DYNAMICS THEORY TO THE THERMAL DOMAIN

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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August 2020

Major Subject: Electrical Engineering

ABSTRACT

This research into thermal systems builds off of multi-domain energy dynamics theory of Prof. Ehsani to gain a clearer understanding and improved model of thermal energy propagation. A review of the general energy dynamics theory is followed by the development of a complete thermal system model from first principles using the electromagnetic domain as the archetype. Comparison is then performed between the traditional laws of thermodynamics and the proposed model to show theoretical consistency where applicable as well as corrections to existing theory.

At the heart of this work lies the fundamental tenet that energy behavior is universally consistent, regardless of in which domain it is observed. Therefore, when energy is observed in a system, certain fundamental properties may be expected. Power exists based on the transfer of energy through space and time. Transfer of energy in any system requires flow, and flow is motivated by an effort. Applying these fundamental ideas of effort and flow to thermal systems yields insights and models, including but not limited to the concepts of thermal resonance and thermal inductance via “gyration” of energy from other domains into thermal and vice versa.

Potential benefits of this research include more accurate models and predictions of thermal transients in physical systems, novel machine concepts and designs patterned after electro-

magnetic systems, in addition to a better conceptual grasp of phenomena, such as the conventional insulation as compared to a thermal resistor.

DEDICATION

To my father Patrick and mother Heidi.

ACKNOWLEDGEMENTS

Foremost, I must thank my Lord and Savior Jesus Christ for His endless grace in providing for and sustaining me through this journey. “I can only say that I am nothing but a poor sinner, trusting in Christ alone for salvation.” – Robert E. Lee

My sincerest gratitude and thanks go to my advisor, Dr. Mehrdad Ehsani, who encouraged me to delve into the abstract and deep waters of original thinking. He consistently provided guidance and solid backup when my thoughts were in disarray. Additionally, he was an excellent friend to swap fishing stories with to lighten the research conversations. May the fish always bite on his line.

Next, I extend my gratitude to my research committee: Dr. Laszlo Kish, Dr. Mark Holtzapple, and Dr. Bhattacharyya. Their classes and research recommendations opened my eyes to concepts that had previously escaped me during undergraduate study. I also must thank the Department of Electrical and Computer Engineering graduate advisors, Katie Bryan and Melissa Sheldon for their unending patience and assistance with class scheduling and other paperwork.

Finally, my love and appreciation for the patience of my family friends and colleagues in the Power Electronics and Motor Drives Laboratory during the past

semesters. They stuck with me through the rough days and long nights of research as well as the happy times rock climbing and playing polo.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Mark Ehsani, Professor S. Bhattacharyya, Professor Laszlo Kish, and Miroslav M. Begovic of the Department of Electrical and Computer Engineering and Professor Mark Holtzapple of the Department of Chemical Engineering.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

Graduate study was supported in part by the Powell fellowship from Texas A&M University, Army Research Lab and a teaching assistantship from Texas A&M University.

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1. INTRODUCTION

1.1. Overview

Six years ago, Multi-Media Energy-Dynamics theory was formally introduced by Prof. Ehsani and his Ph.D. student, Muneer Mohammad, for his doctoral thesis. The core concepts are that power in any domain requires transfer and mutation/transmutation of energy in space and time. In order for this to occur, there must be an effort and a flow present. Referring to the archetype system of electricity and magnetism, this is seen as voltage and current respectively. Where there is flow, something must be considered to be flowing. In the archetype domain, this fluent is electric charge. Fluent in any classical system must be conserved whether it be mass in the mechanical domain or electrical charge in the electromagnetic domain. “The variables necessary to calculate power are the same in functionality: an effort needed to create a movement in a fluent, and a flow or rate at which the fluent moves. Therefore, the power equation can be generalized as a function of these two parameters: effort and flow” [1]

The generalized expression for power in all domains is then taken to be

$$Power = Flow * Effort. \tag{1}$$

Examples of this (flow, effort) pair can be$(Voltage, Current)$, $(Pressure, Volumetric\ Flow\ Rate)$, and $(Force, Velocity)$. From this the generalized pattern of effort and flow emerge. While the physical phenomenon behind voltage has nothing in common with fluid pressure at the macroscopic level, they both attempt to motivate a fluent or conserved quantity to move through space and time (space-time). When the fluent is thus moved, energy is transferred from one point to another.

1.2. Energy

“Energy is a very subtle concept. It is very, very difficult to get right.” [2] In energy dynamics theory, energy is considered to be conserved (nuclear reactions are not considered at this time). As such, energy behaves as a type of book-keeping mechanism. When it is observed to be departing from one system, it must be arriving in another system or systems such that rate of energy out is equal to the combined rate of energy flowing into the other system(s). Grasping the nature of energy is terribly difficult due to its incredibly diverse nature of appearance, “For those who want some proof that physicists are human, the proof is in the idiocy of all the different units which they use for measuring energy.” [2].

1.2.1. *History of Conservation of Energy*

Conservation concepts in science are recorded as far back as ~450 B.C. when Thales of Miletus wrote of earth, air, water, and fire, “Beyond these nothing comes to be or perishes. For if they died continually, no longer would they be. What could increase this whole, and from what source? How too could it be destroyed, since nothing lacks in these? But these are what there is, and running through each other they suffer change continual but always are alike.” [3]

Galileo in 1639 presented a paper noting the mathematical correlation between the drop height of the pendulum and the height to which it will return. This may be seen as the mutation of potential and kinetic energy, though he only recognized the mathematics, not the physics at that time. Christiaan Huygens in 1669 wrote, “Proposition 10: The ratio of the speed which a large body gives to a small body at rest to the speed which a small body of the same speed gives to a large body at rest is the same as the ratio of the magnitude of the large body to the magnitude of the small body.” [4] Here is seen the recognition of conservation between mass and velocity, today known as momentum. Gottfried Leibniz in the 1680s read Huygens’ works and formulated the equation for kinetic energy of a system,

$$\sum_i m_i v_i^2 . \qquad (2)$$

Around the same time, Newton proposed conservation of momentum in his *Principia*. To understand transfer of energy, the “vis viva” concept of spatial energy was coined. The formula for this was

$$\int F\, dt = (mv_1 - mv_2) \qquad (3)$$

where the integral is performed over an interval of time.

Thermal energy was recognized as having a relationship to mechanical systems in 1798 when Count Rumford correlated the temperature rise of cannon barrels being bored with mechanical friction of the boring tool. In 1843, James Joule designed the Joule apparatus which transformed gravitational potential energy into heat. This brought heat and thermal systems under the umbrella of energy studies. Finally, in 1850 William Rankine used the phrase the “law of the conservation of energy”. [5] The key realization from all of this was that there exists some universal “stuffness” which is conserved and with which work can be performed. As such, energy is a scientific algebraic description of a natural phenomenon. [6]

1.2.2. *Forms of Energy*

A Joule of energy is defined as one

$$kg * m^2 * s^{-2}. \tag{4}$$

Examining fundamental dimensions, this is seen to be

$$Mass * Length^2 * Time^{-2}. \tag{5}$$

These dimensions are true of all units of measurement, across all unit systems. This energy can be found across many domains, including but not limited to mechanical, electrical, magnetic, nuclear, gravitational, chemical, and thermal. Mechanical energy includes linear and rotational kinetic energy, potential energy stored in a spring or gas, and other mechanical storage mechanisms. Electrical energy can be found stored in a capacitor. Magnetic energy can be found stored in an inductor. Nuclear energy is energy formed on the basis of splitting or combining atoms. Gravitational energy is stored in potential energy of two masses separated by some distance. Chemical energy is stored within the molecular bonds of a material. Thermal energy or heat is seen as a molecular level kinetic energy. As heat is added to a body, the molecular kinetic energy stored within it increases.

An interesting comparison between linear mechanical kinetic energy, say that of a hammer in motion prior to striking a nail, and that same hammer at rest with the same quantity of energy but in thermal rather than kinetic form, reveals some of the nature of the thermal domain. Upon striking the nail, nearly all the kinetic energy will be released from the hammer and transferred to the nail. Looking at the heated hammer, with similar quantity of energy, its ability to do work is limited by the final temperature at which it will arrive. [7] This result is referred to as Carnot's Theorem, of which more will be said later. [8] In the moving hammer we see all the energy aligned in one dimension of motion. In the heated hammer we see the energy equally distributed into the random motion of all molecules of the metal. The insight gained from this thought experiment is to note that not all forms of energy are equally organized and thereby useful.

1.2.3. *Transformations*

Having recognized that there are many forms of energy and that transformation from one form to another is possible, an examination of these transformations is necessary. Energy transformations are performed usually with the goal of performing a service. These services can range from pumping water to powering a Google server farm. The method for both of these is remarkably similar. In both cases, energy must be taken from some stored form and converted into a kinetic form.

An example, shown in Fig. 1, would be taking the chemical energy stored in diesel fuel and using it as fuel in a diesel engine. The diesel engine then has converted chemical potential energy into kinetic rotational energy at its crankshaft. From there an electric generator again converts the energy from kinetic to electric. This electric energy can finally be sent via transmission line to the server farm. At the server farm, the energy is converted for the last time into thermal energy via I^2R losses. Every conversion of the energy in this long chain contains unspecified losses due to friction, resistance, and non-zero temperature of the diesel exhaust gas such that the amount of energy originally stored in diesel fuel is much greater than the thermal energy dissipated as heat by the server farm.

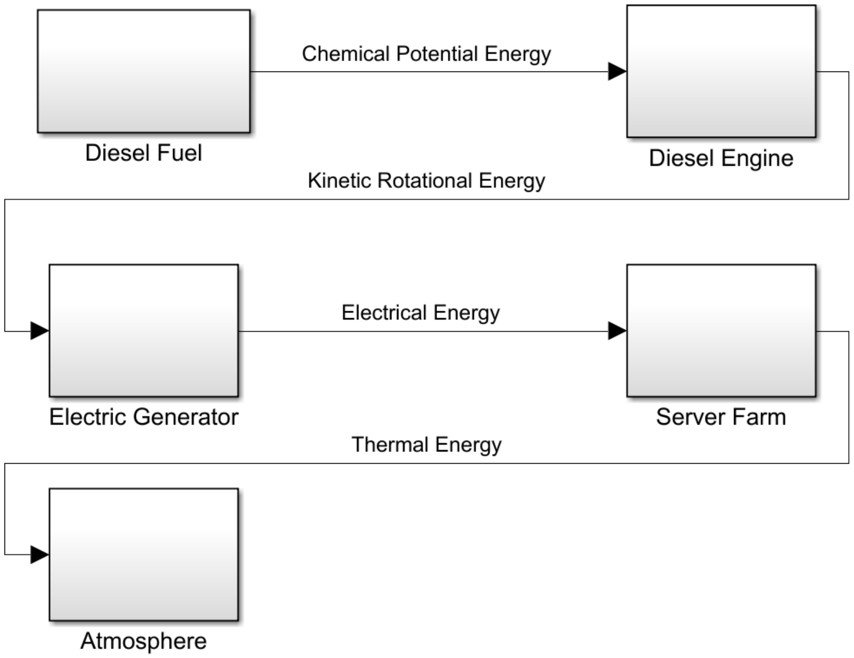

Figure 1.1.1 Energy Conversion Process Example

1.3. *Thermodynamics*

Thermodynamics is the physics of energy in the thermal domain. It describes the relationship between thermal energy, temperature, thermal radiation, and work. Early scientists in the field such as Hermann Helmholtz, Robert Mayer, Sadi Carnot, Rudolph Clausius, and Lord Kelvin all contributed to the field. Their principle reason for working on the subject was improvement of efficiency of the steam engine. The steam engine was literally the prime mover of the industrial revolution, providing the ability for mankind to perform orders of magnitude greater work than in previous generations. Government involvement in the research was also a motivating factor due to France’s involvement in the Napoleonic Wars. [9]

The following is a review of the interactions of temperature and heat transfer as defined in modern thermodynamics.

1.3.1. *Zeroth Law*

The first law of thermodynamics (technically the zeroth law), involves the concept of system equilibrium. “Two systems are said to be in the relation of thermal equilibrium if they are linked by a wall permeable only to heat and they do not change over time.” [10] The zero law states then that “If a system A is in equilibrium with system B, and system B is in equilibrium with system C, then system A is therefore in equilibrium with system C.” At any given equilibrium, a system can be determined to have a specific temperature. While seemingly a simple concept of equivalence, it is vitally important that the temperature be definable and unique such that three systems in equilibrium are guaranteed to be at the same temperature. This permits comparison between systems A and C which may never actually interact with each other. [11]

1.3.2. *First Law*

The real first law of thermodynamics is

$$\Delta U = Q - W \tag{6}$$

where ΔU is the change in energy within the system, Q is the thermal energy going into the system, and W is the energy leaving the system (commonly referred to as work). This law formalizes the conservation of energy. Another way of writing it would be

$$\sum \Delta E = 0 \tag{7}$$

in a closed system.

A side effect of this law is that a perpetual motion machine, wherein energy comes out of a closed system permanently, is technically impossible. Another consequence of this is that if the universe is considered as a closed system, the amount of energy present within it must be finite. Given the theoretically infinite volumetric expansion of the universe, the resulting conclusion is that energy density of the universe will approach zero as time goes on. This is referred to as the “Heat death of the universe.” [12]

1.3.3. *Second Law*

The second law of thermodynamics states that, “the total entropy of an isolated system can never decrease over time, and is constant if and only if all processes are reversible.” [13]

$$\Delta S = Entropy = \frac{\Delta Q}{T} \tag{8}$$

This essentially says that given to systems thermally connected and at different temperatures, the energy will always transfer from the warm system to the cold system until they reach equilibrium of temperature. While mankind has invented air conditioning to circumvent this law at first glance, what is actually occurring is more complicated and does indeed obey this law. This transfer of energy from hot systems to cold systems is the driving factor behind the heat death of the universe, mentioned previously. [12] Also to be noted from the second law, when two systems trans-mutate thermal energy to some other domain for the purpose of doing work, in order to get complete conversion, the second system must be at zero temperature else there will be thermal energy from the first system that is not converted to work. This is referred to as waste heat.

1.3.4. *Third Law*

The third law of thermodynamics states that if a system has a temperature of zero, then it has zero entropy. A simple illustration of this is to consider a room temperature gas. It has some non-zero temperature, and the entropy of it is very high as the molecules are not bound to one another but rather bouncing around the room. Therefore, the entropy can be considered to be high as well. As the temperature of the gas is dropped, it will condense to a liquid and freeze into a solid. At each of those stages, the molecules will become considerably more organized until they tie together into a solid lattice structure wherein the molecules are locked in place but still vibrating. As the temperature theoretically approaches absolute zero, the lattice will cease to vibrate.

1.3.5. *Limitations*

While thermodynamics is certainly a well-developed field filled with powerful tools based on careful observations, it lacks a solid underpinning and background theory. Without this background theory it is limited in its capacity to completely describe various physical systems. In some cases, it may predict an outcome, but not the rate of achieving the outcome or the interim states through which the system will progress. In that sense, it is very good at describing quantitative changes in description. Additionally, thermodynamics at a micro-scale is very divorced from thermodynamics at a macro-scale.

The concept of thermal inductance has been previously approached from a multi-domain perspective [14] but is not considered relevant in most modern thermodynamics simulations and calculations [15]. The thermal inductance concept can be described simply as a mechanism which stores energy when heat energy is actively flowing through a physical medium.

The paper by Bosworth [14] proposes an experiment wherein a conductive wire passes through a known volume of fluid. The temperature of the fluid is monitored as the wire receives a step input of voltage and associated current. This current encounters a resistance in the wire and transfers energy into the fluid thermally according to I^2R, the temperature of the water, and the temperature of the wire. The moment that the current begins to flow, the transmission of thermal energy will be purely in the form of conduction. As the water's temperature begins to increase, convection will occur and the transfer rate of energy into the water will increase. Finally, the water will reach some equilibrium temperature, and energy flow will reach a steady state situation. During the transition to steady state, energy will be stored in the movement of water through convection. Measuring the temperature and flow of entropy, we can calculate the thermal resistance in the system. The description of this can be analogous to two resistors in parallel, the first large and the second smaller but with an inline inductor. When current is initially applied to the wire, the temperature will be greater than the final steady state temperature. If the current is stepped down to some lower value after the convection has begun and reached a steady state of convection, then the wire's temperature can undershoot the final steady state temperature for the new lower current value.

This experiment demonstrates that an inductance behavior can be observed in thermal systems; however, the inductance mechanism is not purely thermal in and of itself as this would violate the second law of thermodynamics [15].

If we could manipulate this inductance to achieve an underdamped situation, then we would predict the temperature of the water to temporarily be greater than that of the wire. Due mainly to the damping characteristics observed, we come to the conclusion that most thermal circuits (TCs) have a very high damping ratio naturally. This is why we do not easily observe temperature transients greater than the wire's steady state temperature.

One final limitation of the currently defined thermodynamics model is the definition of thermal resistance as degrees kelvin per watt (K/W). This limitation will be delved into in the Literature Review section later.

The purpose of this thesis is to propose a complete model for thermal systems that is consistent with the established laws as well as the principles of multi-media energy-dynamics theory and to give illustrative applications of this complete model.

1.4. *Dissertation Organization*

This dissertation is organized in the following manner:

1. A complete definition of the thermal domain in accordance with energy dynamics theory
2. Conceptual experiments to validate the theory and ensure consistency with thermodynamics
3. Examinations of known phenomenon in light of the definitions provided in part 1

1.5. *Contributions*

1. Innovative perspective of thermal systems, including inductive behavior and their transients
2. Improved accuracy for thermal system models

2. LITERATURE REVIEW

2.1. Bond Graph Analysis

One method of analyzing a series of energy conversions is with bond graphs. These graphs attempt to leverage energy’s book-keeping trait at the highest level, looking at the flow of energy between domains [16]. The basic concept of bond graphs, as invented by Paynter, is to represent graphically a physical system using effort and flow as they are classically defined in physics, in conjunction with various junctions and energy storage/dissipation devices.

Bond graphs utilize labeling and direction to graphically represent effort and flow, power, energy conversion, and energy storage. Every process variable within a system is assigned an effort, a flow, and a source and direction for those respectively. This allows for determination of causality for control and mathematical purposes. Cause of effort is depicted by crossing the end of the line next to the variable responsible, and direction of power flow is shown with an arrow on the end of the line. [17]

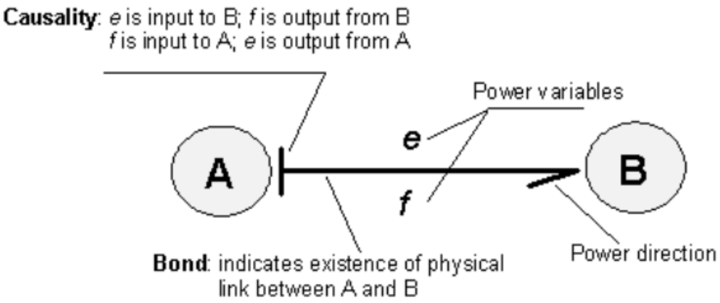

Figure 2.1 Example Bond Graph

While bond graph analysis does correctly show the transfer of energy in principle, it fails to analyze the system dynamics of the effort and flow variables correctly in the thermal domain. This failure is directly due to the incorrect concept of thermal resistance and consideration of convection as a non-linear resistance [17].

2.1.1. *Bond Graph Elements*

Bond graphs are composed of nine base elements [18]. In no specific order, these are as follows:

- Sources of effort (S_e)
- Sources of flow (S_f)
- Inertial element (I)

- Capacitive element (C)
- Resistive element (R)
- Transformer (TF)
- Gyrator (GY)
- 0-Junction
- 1-Junction

The inertial element and the capacitive element both store energy. The resistive element dissipates energy. All three are passive elements. $S_e\ and\ S_f$ are both active elements as they supply power to the system. The final four, $TF, GY, 0\ and\ 1\ Junctions$ all connect sources and act as nodes within the system. TF and GY are both two-port elements across which power is conserved. 0 and $1\ Junctions$ are multi-port elements across which the effort is equal and the flow is equal for all connections respectively.

2.1.2. *Bond Graph Construction*

The construction of a bond graph is done by noting the unique physical mediums through which power is flowing whether they are electrical, thermal, chemical, mechanical, and so on. The flow and effort of each medium is analyzed, and boxes are drawn out to depict the physical layers from which each originates. It is important that the direction of power flow be properly determined at this stage. Once this is completed, the boxes are then labeled as the appropriate element. Having drawn out the initial system, then the necessary passive elements can be added. Once this is accomplished, causality must be established; then a state-space equation series with first order differential equations can be derived. These equations are the basis for a state space controls system model.

2.1.3. *Thermal System Example Utilizing Bond Graph Theory*

The following example, including images, is summarized from Gordana Janevska's paper, "*Bond Graphs Approach to Modeling Thermal Processes*." It is summarized here to show the construction and evolution of a bond graph example. The system to be depicted via bond graph is as shown in Figure 2.2. [17]

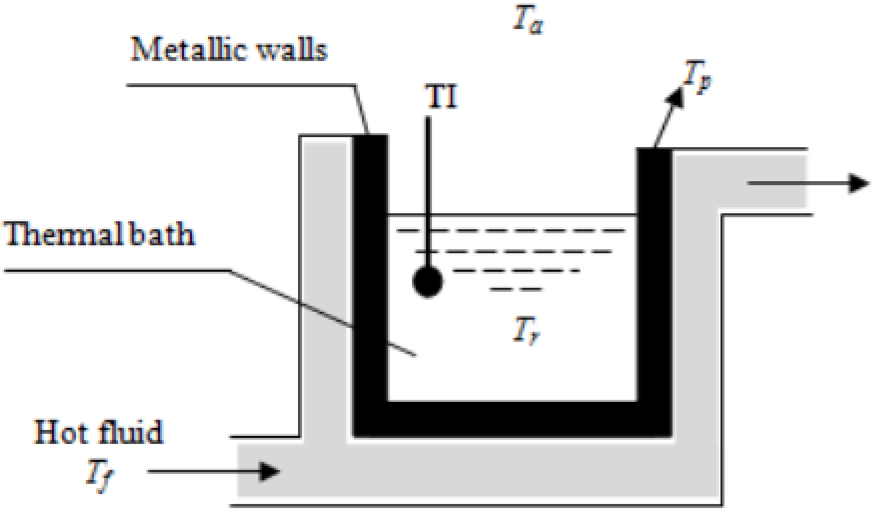

Figure 2.2 Example Thermal System

This example system is a volume of bath water in a metal bathtub, heated by a hot fluid. Here thermal energy will be transferred from a constant flow source, to the hot fluid, to the metal bathtub wall, to the water in the tub, and finally to the environment a constant effort (temperature) source. The first step of drawing boxes depicting the system, effort, and flow is then as seen in Figure 2.3 [17]

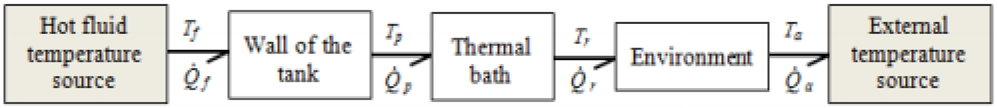

Figure 2.3 Bond Graph Step 1

Next the boxes are converted to elements and passive elements added as necessary as shown in Figure 2.4 [17].

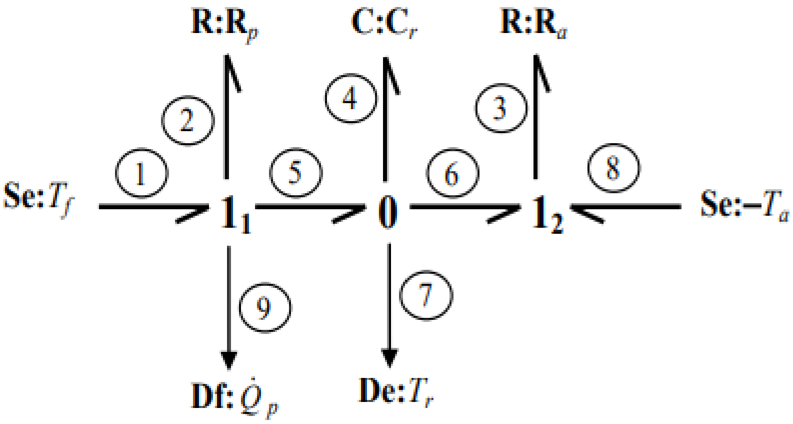

Figure 2.4 Bond Graph Step 2

Now causality must be added as seen in Figure 2.5 [17].

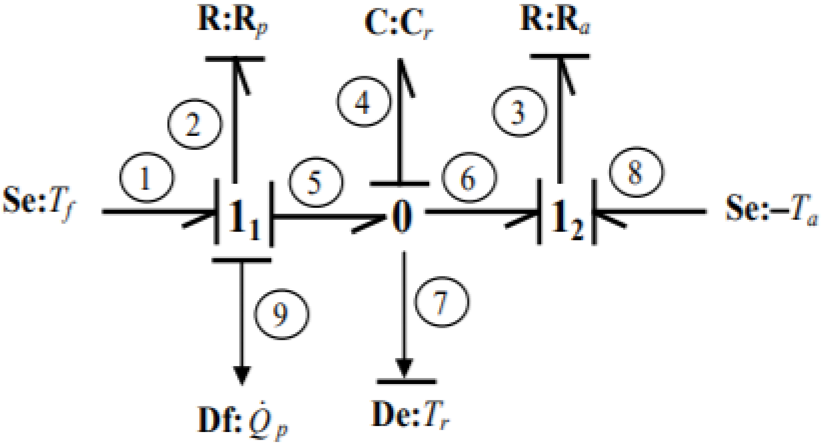

Figure 2.5 Bond Graph Step 3

At this point the differential equations for the system can be derived visually as follows:

For Junction 1_1, $e_2 = T_f - e_5 \ and \ f_1 = f_5 = f_9 = \ Q_p \overset{\cdot}{=} f_2$ (9)

For Junction 0, $\dot{Q}_4 \ = f_4 = f_5 - f_6 \ and \ e_5 = e_7 = e_6 = T_r = e_4$ (10)

For Junction 1_2, $e_3 = e_6 - T_a \ and \ f_8 = f_6 = f_3$ (11)

For R: R_p, $f_2 = \frac{1}{R_p} e_2 = \frac{T_f - e_5}{R_p}$ (12)

For C: C_r, $e_4 = \frac{1}{C_r} \int_0^t f_4 dt + e_4(0) = \frac{Q_4}{C_r}$ (13)

For R: R_a, $f_3 = \frac{1}{R_a} e_3 = \frac{1}{R_a}(e_6 - T_a)$ (14)

In these equations, C_r is the global thermal capacity as defined traditionally in thermodynamics by

$$C_r = m_r c_v \tag{15}$$

where m_r is the constant mass of the total fluid and c_v is the constant volume of the global fluid. $R_p and\ R_a$ are the thermal resistances (traditionally defined) of the hot fluid to tub wall interface to water interface and then the water to environment interface, respectively. The state space equations then take the form:

$$x = Q_4 = Q_r, \tag{16}$$

$$u = \left[T_f \ \ T_a\right]^T, \tag{17}$$

$$y = \left[Q_p^{\cdot}\, T_r\right]^T, \tag{18}$$

and the control system diagram is as shown in Figure 2.6 [17]

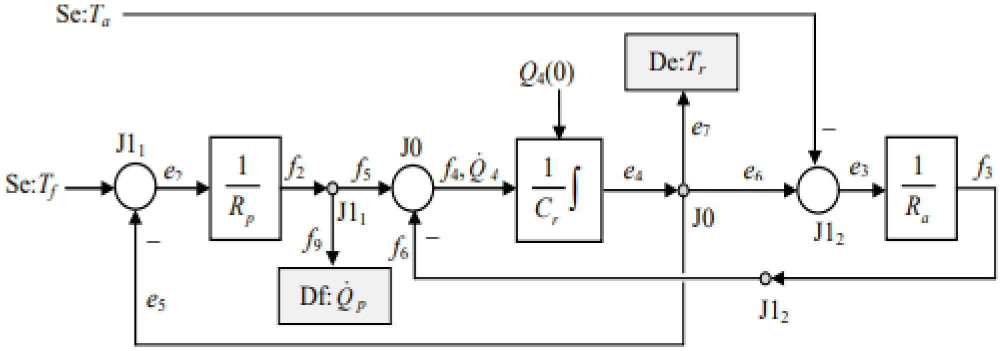

Figure 2.6 Thermal Control System

2.1.4. *Fundamental Bond Graph Conclusions*

From this example it is seen that the bond graph modeling technique is an excellent tool for exploring multi-domain physical systems based on the concepts of effort and flow. The problem with bond graph analysis in the thermal domain is the description of the thermal dissipative element "R" as being the "reciprocal of the heat transfer coefficient K_c" [17]. The heat transfer coefficient of a material is defined as having units of $\frac{W}{m^2K}$ [15]. Taking these units and substituting them into the equation,

$$R: R_p, f_2 = \frac{1}{R_p} e_2 = \frac{T_f - e_5}{R_p}, \tag{19}$$

the result is that f_2 has units of power (W) rather than units of thermal current $(\dot{Q})$. Thus, when f_2 is multiplied with e_2, the results are not the power units that are needed for a correct accounting of energy flow through the thermal system. The Multi-Media Energy-Dynamics Theory as presented in the next section of this thesis proposes to correct this physically meaningless concept of thermal resistance and to introduce the missing concept of thermal inductance.

3. ENERGY DYNAMICS

3.1. *Research Objectives*

The definition of the classical thermal domain has been considered complete and mostly unchanged at the macroscopic level since 1906 when Walther Nernst stated the third law of thermodynamics: “The entropy of a perfect crystal at absolute zero is exactly equal to zero*”* [19]. The major discoveries from that point trended in the direction of quantum mechanics, courtesy of Einstein and his theory of mass-energy equivalence.

The modeling and mathematics of the thermal domain based on classical thermodynamics contain several discrepancies when compared with energy dynamics as observed in other domain models such as electrical, mechanical, fluid, and so on. Additionally, thermodynamics fails to provide answers to several questions where nuclear physics becomes involved [20] [21]. The following is a partial list of some of these discrepancies and questions.

1. How is entropy in an electrical circuit properly viewed and calculated?
2. On what basis is the second law of thermodynamics formed?
3. Why does thermal resistance have units of rate of change entropy?
4. Why does the Carnot efficiency limit exist?

These questions are a few examples of the incomplete background of thermodynamics and the models that have been developed through its applications. Resolving these discrepancies and answering these questions will provide us a new platform from which to engineer the next generation of modeling simulations. From there, innovative machine architectures can be conceived and then built [22].

3.2. *Proposition and Motivations*

The Multi-Domain (or multi-media) Energy-Dynamics theory states that “Energy must behave the same in all its forms and in every domain that it may reside” [1]. Taking advantage of the Energy-Dynamics unified theory, this thesis proposes to correct the domain of thermal systems to match the patterns found in every other field of energy studies.

The motivation for this work is simple. We wish to provide a more stable foundation for thermodynamics moving forward into the twenty-first century.

In order to accomplish this, the well-known and accepted mathematical pattern of the archetype domain (Electricity and Magnetism) will be applied here to the thermal domain. As such, Maxwell’s equations and circuit theory analogies will be utilized as tools of grasping and properly defined?ing thermal systems. From this corrected definition will come improved modeling and design of everything from automobile radiators, thermal conductors at solar electricity generating plants, aircraft engine thermal signatures, and many other advanced applications.

3.3. *Archetype Review*

A brief review of the archetype domain (Electricity and Magnetism) in Energy-Dynamics will be our starting point prior to making application into the thermal domain. A first definition is the concept of an energy source as a container in which energy exists. This container is taken to hold a finite quantity of energy and is taken as the reference frame such that the container does not move in space nor change in time. How and why the energy came to be present under such circumstances does not matter; it only matters that the energy is there now. This energy container can manifest itself in a large variety of ways such as a compressed spring, a heated object, a charged capacitor, a charged inductor, a spinning flywheel, and so on. We consider each of these examples to be energy sources in different domains.

In the electrical domain, charge (q) is considered to be the fluent or conserved and defining quantity of the domain, much as mass is the fluent of the mechanical system and dollars are the conserved quantity of the financial system. In addition to being a conserved quantity, the electrical charge produces an electric field through which other charges can interact with it without direct physical contact. This field produces on other charges a force or effort as shown in Figure 3.1.

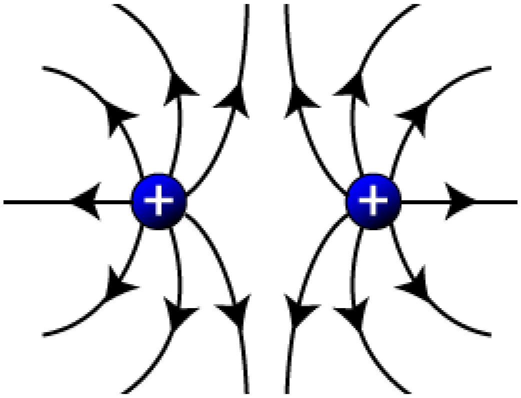

Figure 3.1 Electric Field of Two Positive Charges

In this figure it is seen that two like charges will repel each other as based on their electric field lines diverging. This field is defined as

$$\vec{E} = \frac{q}{4\pi\varepsilon r^2}\vec{r}, \tag{20}$$

where q is the electric charge, ε is the electrical permittivity of the material in which the charge resides, and $\vec{E}$ is the electric field strength at some distance $\vec{r}$ from the charge's location.

In order to determine the presence of an electric field, a known quantity of charge must be placed at the point of measurement. If there is another charge nearby providing an electric field, then their fields will interact according to

$$\vec{F} = q_{test}\vec{E}. \tag{21}$$

That is to say that the electrical field (if there is one present) will apply an effort of force to the test charge. This force will have dimensions of $Mass, Length, and\ Time^{-2}$. The field causing the force will then have dimensions of $Length\ and\ Time^{-2}$. From this we observe the universality of effort, space, and time. Also noteworthy is the unique permittivity of the domain ε. When a positive and negative charge are separated, the force required to do so taken as an integral across the distance of separation is taken to be stored electrical energy. Mathematically, this stored energy is

$$W_e = \int \overrightarrow{F_e . d\vec{r}}. \tag{22}$$

When charge q is moved through space, this is referred to as flow or current. At a fixed point in space, the rate of passing of charge in time, or current, becomes

$$I = \frac{dq}{dt}. \tag{23}$$

This assumes uniform velocity of charge flow, constant electric field, and fixed geometry of the medium through which the current is flowing. The current density $\vec{J}$ and the electric field are related by the resistivity of the material, ρ. Mathematically,

$$\rho = \frac{\vec{E}}{\vec{J}}. \tag{24}$$

This is known as Ohm's law after Georg Ohm [23]. When examining a charge carrying wire, the expression for resistivity can be expressed as

$$\rho = \frac{AV_e}{dL} \tag{25}$$

where A is the cross-sectional area of the wire and L is the length of the wire. To arrive at the more familiar equation,

$$R = \frac{V}{I} \tag{26}$$

note that

$$\frac{V}{I} = \frac{L}{A}\rho, \tag{27}$$

thus

$$R = \frac{L}{A}\rho. \tag{28}$$

When multiple charges of same sign are packed into an enclosed region, they will establish a field with a given strength; a certain amount of electro-voltaic potential will be required to accomplish this packing,

$$\frac{A}{d}\varepsilon = \frac{q}{V} = C. \tag{29}$$

Assume positive and negative electric charges are separated in the simple geometry of two parallel conductive plates. Three phenomena are observed. First, an electric field is established between the parallel plates, in volts/meter. Second, potential energy is stored in this electric field. Third, depending on the separation between the plates, a voltage is established between the plates. This voltage is proportional to the amount of charge that is on each plate:

$$q = Cv. \tag{30}$$

The constant of this proportionality can be defined as the electric capacitance in this parallel plate geometry. This proportionality constant or capacitance, C, depends on the geometry and separation medium of the parallel plates as follows.

$$C = \frac{A}{d}\varepsilon \tag{31}$$

Further, the p energy in this parallel plate capacitor is associated with the positive charge traversing the electric field between the plates, or traversing the voltage field from zero to v:

$$\mathrm{W} = \int_0^v q dv = \int_0^v C v dv = \frac{1}{2} C v^2 \tag{32}$$

This is the concept of capacitance: stored energy within the closed space due to some density of charges present within that space that are repelling each-other.

3.4. Gyrator Theory

Invented in 1948 by Bernard Tellegen as a fifth circuit element to go along with resistors, capacitors, inductors, and transformers, its primary description is a two-port lossless network wherein the voltage on port one is proportional to the current on port two, and the current on port one is inversely proportional to the voltage on port two. The circuit drawing representation of a gyrator is shown in Figure 3.2.

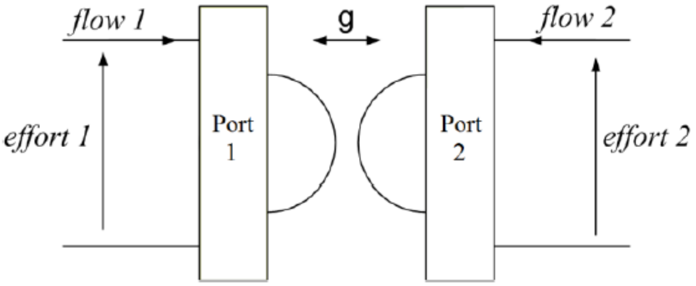

Figure 3.2 Gyrator Element

The mathematical description of a gyrator then must be

$$Effort_1 = -g * Flow_2 \tag{33}$$

and

$$Effort_2 = g * Flow_1. \tag{34}$$

where voltage is represented by $Effort$ and current by $Flow$.

At this point, $V, I, R, and\ C$ have all been introduced as fundamental properties of the electric domain. By applying Faraday and Ampere’s laws, energy mutates into the magnetic domain through gyration.

$$V = -N\frac{d\varphi}{dt} \tag{35}$$

and

$$mmf = NI. \tag{36}$$

Equations (35) and (36) describe a gyrator relationship, as defined above.

With $g = N$ in this case, it is seen that mmf and $\frac{d\varphi}{dt}$ are the effort and flow respectively of the magnetic domain [24] [1]. With $\frac{d\varphi}{dt}$ as the flow of the magnetic domain, then the fluent or charge must be φ. Having defined flow, effort, and charge, the magnetic resistance is then seen properly as

$$\frac{mmf}{I_m} = \rho_{magnetic}\frac{L}{A}\,. \tag{37}$$

Finally, the capacitive element of the magnetic domain must be

$$C_m = \frac{flux}{mmf} = \mu\frac{A}{L}\,[1]. \tag{38}$$

In this we see that an inductance phenomenon in the electrical domain is actually a capacitance coming through from the gyrated magnetic domain where

$$L = g^2 C_{magnetic}. \tag{39}$$

We can describe this through the circuit model shown in Figure 3.2.

Because energy gyrates between the electric and magnetic domain without loss, the magnetic domain is referred to as the co-domain of the electric domain.

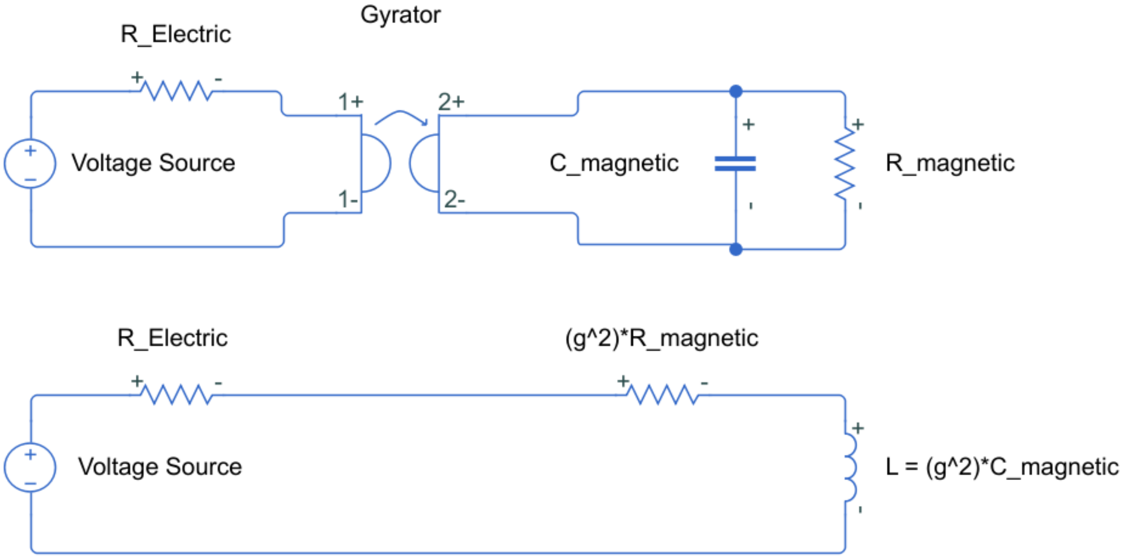

Figure 3.3 Circuit Model of E & M Gyration

Shown in the upper model above is an electro-magnetic circuit model based on Energy Dynamics Theory. Note that the electric domain is on the left and the magnetic or co-domain on the right. They interact through a gyrator as described above with a resulting combined behavior as shown in the lower model. This is a simple example of how gyration explains inductive behavior in one domain via a capacitance in a co-domain.

4. THERMAL DOMAIN APPLICATION

4.1. Thermal domain

The starting point for examining the thermal domain is to assign temperature as the force or effort in the domain. This is logical because a difference in temperature between two objects will lead to a transfer of thermal energy, exactly as the difference in voltage causes electrical energy flow in the electric domain. Just as the unit of charge in the electrical domain is defined as energy/effort (Joules/Volts), so the unit of charge within the thermal domain is taken to be Joules/Temperature. This, in fact, is what is defined as entropy in thermodynamics. With entropy, s, as the state variable or fluent of the thermal domain, then flow of entropy is formulated to be

$$I_{th} = \frac{ds}{dt}\ [\frac{Joules}{Temperature * Time}]. \tag{40}$$

Effort, fluent (thermal charge) and flow of the thermal domain having been defined; the next step is to find the definition of resistance as $R_{thermal} = \frac{Effort}{Flow}$.

This gives

$$R_{thermal} = \frac{T}{\frac{ds}{dt}}\left[\frac{T^2 t}{Joules}\right] \tag{41}$$

where T is temperature and t is time.

To complete the basic elements of the thermal domain in accordance with Energy-Dynamic theory, there must be a capacitive energy storage element. Thermal capacitance must be a measure of energy stored in the thermal medium due to a given increase in temperature. This can be described mathematically as

$$w = \frac{1}{2}Cv^2 \Leftrightarrow w = \frac{1}{2}C_{th}T^2 \text{ (period?)} \qquad (42)$$

Further:

$$q = Cv \Leftrightarrow C = \frac{q}{v} \Leftrightarrow C_{thermal} = \frac{s}{T}\,[\frac{Joule}{T^2}]. \qquad (43)$$

Thermal capacitance will then be dependent on the geometry of the medium and the intrinsic thermal constant of the material (a new material science constant definition), analogous to the electrical dielectric of the electrical medium. In a simple thermal medium geometry example of a three-dimensional rectangle:

$$C_{thermal} = \frac{\varepsilon_{thermal}A}{l} \qquad (44)$$

where A is the cross-sectional area, l is the length of the thermal conductor, and $\varepsilon_{thermal}$ is the thermal permittivity of the material.

A summary of the above derivations, based on the Energy Dynamics theory is shown in Table 1.

Table 1 Thermal Domain State Variables

Fluent or Conserved Quantity	$q_{thermal} = s\ [\frac{Joule}{T}]$
Effort Description	$Effort_{thermal} = T\ [T]$
Flow Description	$I_{thermal} = \frac{ds}{dt}\ [\frac{Joules}{Tt}]$
Dissipative Element	$R_{thermal} = T/\frac{ds}{dt}\ [\frac{T^2 t}{Joules}]$
Energy Storage Element	$C_{thermal} = \frac{s}{T}\ [\frac{Joule}{T^2}]$

A quick analysis to check our conclusions thus far shows:

1. $Effort_{th} * Flow_{th} = T * \frac{Joules}{Tt} = Watts$
2. $Flow_{th}^2 * R_{th} = \frac{Joules^2}{T^2 t^2} * \frac{T^2 t}{Joules} = Watts$
3. $\frac{Effort_{th}^2}{R_{th}} = T^2 * \frac{Joules^2}{T^4 t^2} * \frac{T^2 t}{Joules} = Watts$

These quick and simple checks demonstrate that our thermal domain definitions are consistent with Energy-Dynamics theory by correctly resulting in units of power for the three equations.

A key takeaway from this derivation is the concept of entropy flow. While thermal energy (traditionally heat) certainly does flow through materials, the missing concept of flow of entropy has led to a great deal of misunderstanding and mischaracterization of the thermal domain. Problem one of classical thermodynamics is taking heat as the fluent. Problem two is derived from problem one and is the classical definition of thermal resistance as being that property of a material which resists transfer of energy through it. The simple multiplication of heat flow with temperature proves that the utilization of heat as the thermal fluent has been incorrect as it does not result in units of power. As shown above, the Energy Dynamics definition of thermal fluent will pass this test that classical thermodynamics fails. With the proper definition of thermal fluent, the true thermal resistance can then be understood through the relation of effort and flow.

4.2. Co-Thermal Domain

In accordance with Energy-Dynamics theory, for every domain there must be a co-domain. In the architype domain, the electric domain is coupled through a gyration with the magnetic domain. Similarly, the thermal domain must interact with a co-thermal domain through gyration. According to the Energy Dynamics theory, energy domains are either primary (such as electromagnetic or gravitational) or composite (such as thermal, acoustic, pneumatic, hydraulic, etc.). The co-thermal domain must be a composite co-domain, due to thermal being a composite domain.

As a reminder, the mathematical relationship between domain and co-domain according to Energy Dynamics is

$$Effort_1 = -g * Flow_2 \tag{33}$$

and

$$Effort_2 = g * Flow_1. \tag{34}$$

Starting with (33) to find the co-thermal flow and taking the thermal domain as the first domain,

$$I_{cothermal} = -\frac{1}{g} Effort_{thermal} \, [T]. \tag{45}$$

Next, utilizing (34) to determine the co-thermal effort,

$$Effort_{cothermal} = g * I_{thermal} \, [\frac{Joules}{Tt}]. \tag{46}$$

The co-thermal dissipative element according to (26) must be,

$$R_{cothermal} = \frac{Effort_{cothermal}}{I_{cothermal}} \, [\frac{Joules}{T^2 t}]. \tag{47}$$

Given (23), then the fluent, conserved quantity, or charge of the co-thermal domain must be,

$$q_{cothermal} = \int I_{cothermal} \, dt \, [Tt]. \tag{48}$$

And finally, to complete the co-thermal domain using (29), the co-thermal capacitive element can be described by,

$$C_{cothermal} = \frac{q_{cothermal}}{Effort_{cothermal}} \, [\frac{T^2 t^2}{Joules}] \tag{49}$$

The co-thermal domain definitions are summarized in Table 2.

Table 2 Co-Thermal Domain State Variables

Fluent or Conserved Quantity	$q_{cothermal} = thermal\,flux\ [Tt]$
Effort Description	$Effort_{cothermal} = g * I_{thermal}\ [\frac{Joules}{Tt}]$
Flow Description	$I_{cothermal} = -\frac{1}{g} Effort_{thermal}\ [T]$
Dissipative Element	$R_{cothermal} = \frac{Effort_{cothermal}}{I_{cothermal}}\ [\frac{Joules}{T^2 t}]$
Energy Storage Element	$C_{cothermal} = \frac{q_{cothermal}}{Effort_{cothermal}}\ [\frac{T^2 t^2}{Joules}]$

A quick analysis to check our co-thermal conclusions thus far shows that:

1. $Effort_{coth} * Flow_{coth} = g * I_{thermal} \left[\frac{Joules}{Tt}\right] * -\frac{1}{g} Effort_{thermal}\ [T] = Watts$
2. $Flow_{coth}^2 * R_{coth} = \left(-\frac{1}{g} Effort_{thermal}\ [T]\right)^2 * \left(\frac{Effort_{cothermal}}{I_{cothermal}}\ [\frac{Joules}{T^2 t}]\right) = Watts$
3. $\frac{Effort_{coth}^2}{R_{coth}} = (g * I_{thermal}\ [\frac{Joules}{Tt}])^2 * \left(\frac{Effort_{cothermal}}{I_{cothermal}} \left[\frac{Joules}{T^2 t}\right]\right)^{-2} * \left(\frac{Effort_{cothermal}}{I_{cothermal}}\ [\frac{Joules}{T^2 t}]\right) = Watts$

Once again, all of these relations are consistent with Energy Dynamics and correctly result in the dimension of power. This completes the description of the thermal domain and co-domain elements from the perspective of Energy Dynamics Theory.

Grasping the meaning of these co-thermal elements can be challenging as they have not been considered from this perspective in any previous discipline. The concept of the conserved co-thermal charge being thermal flux with units of $Temp * Time$ is best grasped by comparing with magnetic flux. When viewed in this manner, one starts to see the pattern.

4.3. *Inductance Through Gyration*

In the archetype system, electrical inductance was shown to be the gyration of magnetic capacitance. The same behavior holds true between the thermal and co-thermal domains. In this case, the co-thermal domain is another composite domain, as mentioned previously, and is a dual of the thermal domain, as seen from the thermal domain side. Thus a “thermal inductance” effect, as described in 1.3.5, is one example of a composite energy domain providing a “thermal capacitive” storage element in the co-thermal domain, or alternatively, a “thermal inductive” storage element when viewed from the thermal domain side. This is most easily understood through a circuit model as shown in Figure 3.3

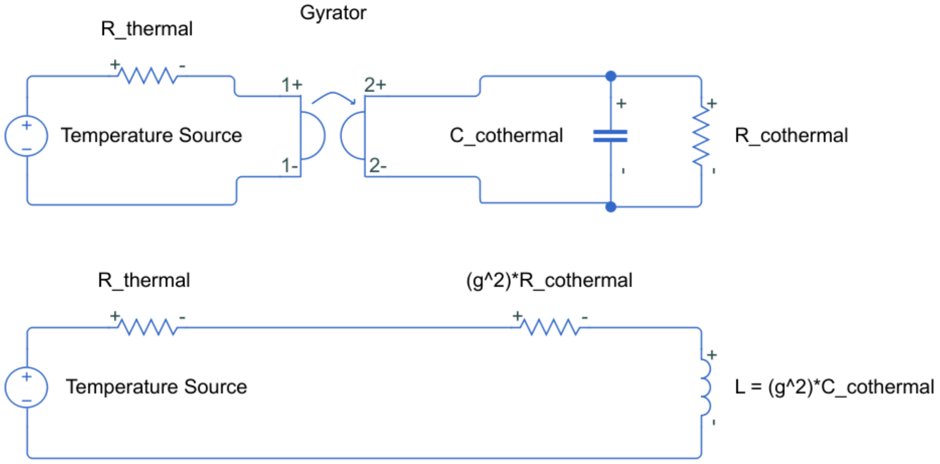

Figure 4.1 Model of Thermal and Co-thermal Gyration

Because the thermal and co-thermal are both composite domains being viewed at a statistical level, the gyration between them will be some combination of microscopic effects. In a similar way, a hydraulic system composed of molecular-level forces in lattices to constrain fluids experiences the fluid hammer inductance effect. Energy Dynamics makes predictions and describes the macroscopic behaviors of energy, regardless of the specific medium; and this is no different in the thermal domain. The convection which occurs during thermal energy transfer between a solid and a liquid is a microscopic driver of the macroscopic thermal induction effect.

Another gyration of the thermal domain is with the mechanical domain, through the expansion of gasses at some mechanical pressure. Thermal energy is converted to mechanical energy through a gyration. Examining a gas contained in a non-fixed volume container which is then heated to a higher temperature, the thermal energy input will be split between the capacitive storage of the thermal domain (temperature increase) and the inductive storage of the mechanical domain (volume increase). This is referred to as Charles' Law of Temperature and Volume [10]. Any increase in temperature of the thermal system will be directly proportional to increase in volume in the physical system. Put another way, the mechanical flow will be proportional to the thermal effort,

$$Effort_{Thermal} \propto Flow_{Mechanical} \tag{50}$$

Once again, this gyration occurs at a macroscopic level due to the thermal domain being a composite domain.

4.4. *System Energy Losses*

In the archetype domain of electricity and magnetism, there are multiple sources of energy dissipation in the system including, but not limited to, resistive heating, skin effect, and magnetic losses. The main sources are the resistive heating described by I^2R and the magnetic loss described by $I^2N^2R_{magnetic}$. Taking these concepts and applying them to the thermal domain, there appears to be a gyration occurring wherein power is being gyrated from the electric domain to the thermal domain. The power out of the electric domain and going into the thermal domain is:

$$I_{electric}^2 R_{electric} \tag{51}$$

If we take this and integrate it across a given time period, we will arrive at a certain amount of energy that must be now present in the thermal domain. Thermal energy storage is done through temperature change in a thermal capacitor. The governing equation for this is:

$$w = \frac{1}{2} C_{th} T^2 \tag{42}$$

Combining the integration of (50) with (42),

$$\frac{1}{2} C_{th} T^2 = I^2 R t \tag{52}$$

Rearranging to solve for T,

$$T = I \sqrt{\frac{2Rt}{C_{th}}} \tag{53}$$

Taking the radical portion of the equation as g from (34), it is clear that this is indeed a gyration. This is taken as further evidence of the thermal domain being a composite domain.

The key in power loss calculations is that it in any domain it is always found to be proportional to the flow to some (varying) power. In the mechanical domain for example, depending on the conditions, the losses can be of the windage, stiction, or coulombic variety, all of which depend on the velocity where velocity is a dependent function of effort. Thus, the power dissipated in the mechanical domain is also seen to be contingent upon effort to varying exponents. A similar conclusion may be drawn for the archetype domain wherein I is a dependent function of effort (V).

In thermal systems, the energy lost to radiation is related to temperature by the Stefan-Boltzmann law,

$$j = \sigma T^4 \tag{54}$$

Resulting from this, within a body of uniform temperature there will be no thermal radiation. This is in alignment with Energy Dynamic's prediction of thermal domain energy losses being related under certain conditions by

$$P_{loss} = k\, I_{thermal}^{x} R_{thermal} \tag{55}$$

where x is a power dependent on various physical factors not currently described in traditional thermodynamics. In order for P_{loss} to equal zero according to (50), then $I_{thermal}$ must be equal to zero in (51). There will be no flow of entropy only when no temperature difference exists within the system, also known as uniform thermal body.

4.5. *Entropy as Fluent*

Having taken entropy to be the fluent, conserved quantity, and charge of the thermal domain, the question must be answered: What about creation/destruction of entropy? The key to answering this lies in the composite nature of the thermal domain and is best illustrated through a simple analogy. Let us consider a fictitious "domino domain." This domain would be composed of dominoes all standing up on end and in a line such that when one is knocked down, the rest follow in short order. In this way, energy imparted at one end will appear after some time at the far end of the dominoes. This is a great example because it is clearly a composite domain with the fluent being dominoes. In the same way that adding or removing a domino from either end of the system adds or subtracts fluent, so fluent can be added or removed from thermal systems. Methods through which entropy can be added to a thermal system include exothermic chemical reactions, electrical charging of a capacitor, magnetic charging of an inductor, nuclear reactions, and so on. Likewise, an endothermic reaction, discharging of a capacitor, inductor, and so on, can remove entropy from a system.

Mathematically, the addition and removal of entropy from a thermal system can be described by referring to the definition of entropy,

$$\Delta S = Entropy = \frac{\Delta Q}{T} \tag{8}$$

Here we see that indeed addition or subtraction of energy can result in change of entropy. This is similar in the archetype domain to,

$$Q_{electric} = W/V \tag{56}$$

where it is seen that energy can be added to an electric system either by adding electric charge or by increasing the voltage of the system. If we define our system as having a definite and fixed amount of charge, then any energy put into the electrical system must result in an increase in voltage, and any energy put into the thermal system must result in an increase in temperature.

4.6. *Thermal Transmission System*

In similar fashion to the transmission line model used in electrical circuits, a heat transfer model of distributed elements can be developed to describe a thermal system through which heat is transported. The simplest example of this would be a copper bar with two temperature sources, T_1 *and* $T_{2,}$ one located on each end of the bar. T1 may be a solar energy collector connected through a thermal conductor to a steam generator acting as a thermal load at location T2. The portion of the copper bar which is not exposed to either of the temperature sources is taken to surrounded?? by some mechanical fluid or gas capable of convection. In this design, the thermal resistance, capacitance, and inductance would be determined by the length of the copper bar as follows.

$$R_{tl} = \frac{T^2}{Wl} \tag{57}$$

Likewise

$$L_{tl} = \frac{t^2 T^2}{Joulel} \tag{58}$$

And

$$C_{th} = \frac{Joule}{lT^2} \tag{59}$$

Building these in a thermal transmission model to view the temperature of the bar at multiple points, as well as to predict power transmission to the load, results in the model seen in Figure 4.2,

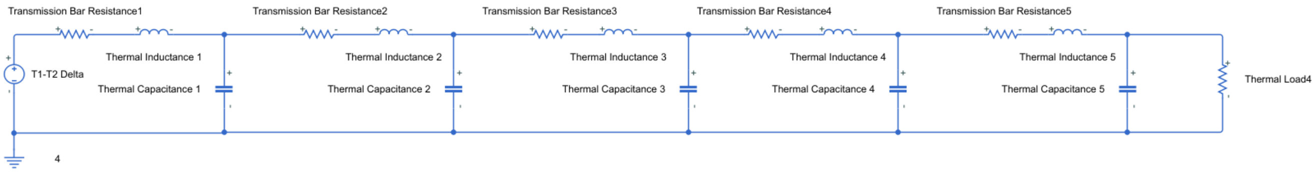

Figure 4.2 Thermal Transmission System

Simulating this using model in Simulink gives a power delivery profile as seen in Figure 4.3 where time in seconds is on the horizontal axis and power is on the vertical axis.

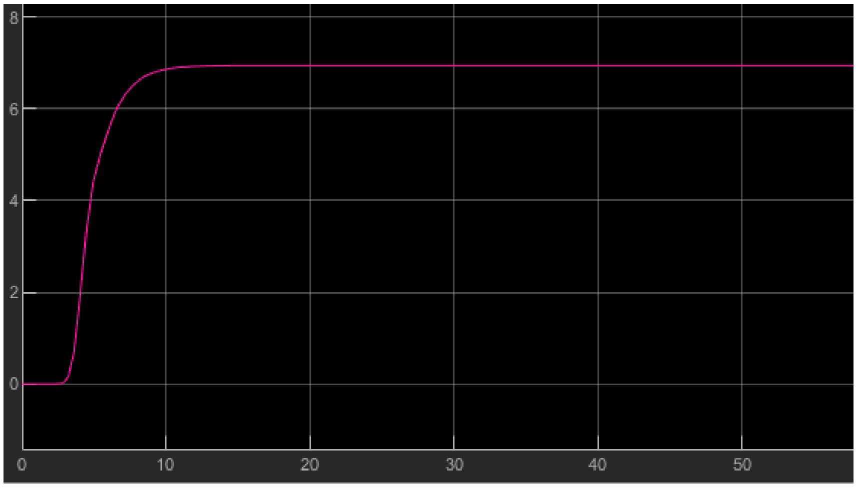

Figure 4.3 Power Delivery Energy Dynamics

If we compare this with the classical differential equation model, we will see that the classical model erroneously predicts an oscillation in the power delivery under steady state conditions.

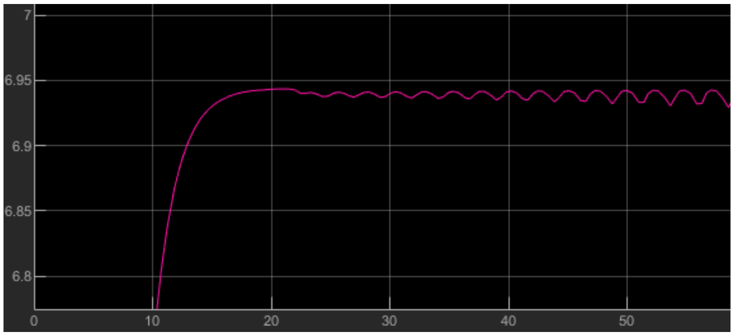

Figure 4.4 Power Delivery ODE Model

Between the two is a clear illustration of the power of the Energy Dynamics model to more accurately model thermal systems.

If the previous example system is modified to include an oscillation in the temperature source T1, as would happen due to the sun setting and rising throughout the course of a day, another phenomenon can be witnessed further demonstrating that classical thermodynamic modeling lacks an understanding that Energy Dynamics provides. This comes through the wave transmission speed equation which can be adapted from the archetype domain as,

$$\gamma = \sqrt{(R_{th} + j\omega L_{th})(G_{th} + j\omega C_{th})} \tag{60}$$

Where $\omega = 2\pi f$, G_{th} is the number of conducting segments per unit length, and f is the frequency of the wave. The equation for wave speed given in (60) is patterned after a similar equation for wave speed in the mechanical domain derived in [1]. From this wave speed equation, it is clear that the induction effect predicted by Energy Dynamics will increase the wave speed propagation. This is true not only of wave transmission, but also of the time between temperature steps and other interruptions to the energy input at T1 and those perturbations appearing at the load T2.

5. EXPERIMENTS AND VALIDATION

5.1. *Bond Graph Modeling Re-examined*

Having completed the model of the thermal domain, the first application of it will be to the bond graph example given in the literature review. A thermal circuit model based on Energy-Dynamics will be demonstrated and explored.

To begin with, the bond graph as proposed in the paper is as shown in Figure 5.1.

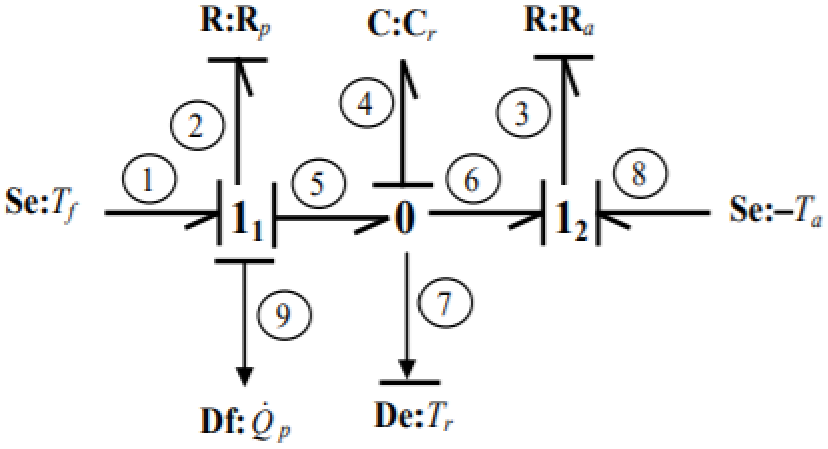

Figure 5.1 Thermal Example Bond Graph

Type 1 junctions have equal flow and type 0 expresses equal temperature. Junction 1_1 is describing the entropy flow from the effort source on the far?? going through the resistance R_p and being observed by $\dot{Q}_p$. Junction 0 is describing the temperature of the water observed by T_r as well as the energy stored capacitively in the thermal capacitor C_r. Junction 1_2 described the flow of entropy leaving the water into the atmospheric effort source T_a through some resistance R_a. A Simulink model of this bond graph is shown in Figure 5.2

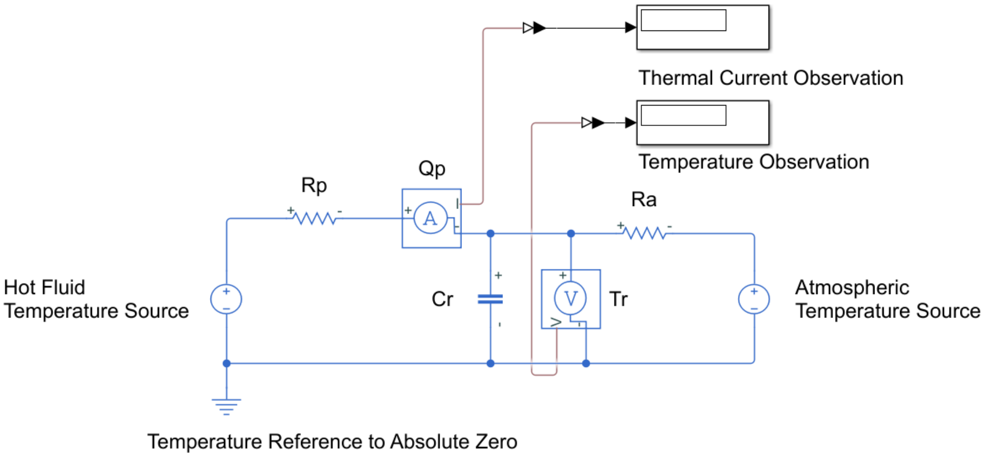

Figure 5.2 Thermal Circuit Model

This is easily simulated in MATLAB and shows several conclusions, all of which are intuitive when thinking of the physical system. A temperature versus time profile for the water in the system is shown in Figure 5.3

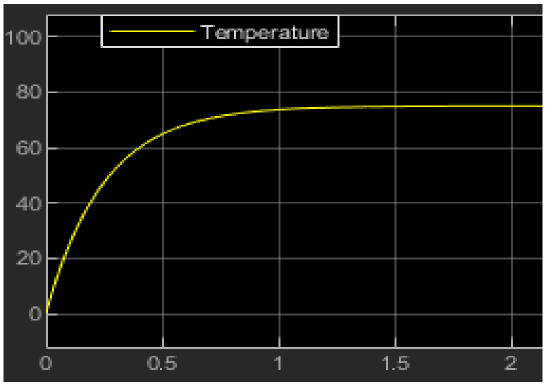

Figure 5.3 Temperature Profile of Simple Model

Noteworthy conclusions from this model are:

1. The final temperature of the water is dependent on two properties: the temperature difference between the heating fluid and the atmosphere and the ratio of the two thermal resistances.
2. The time taken to arrive at steady state temperature is dependent on the magnitude of the combined thermal resistances and the thermal capacitance of the water.
3. The temperature is asymptotic in its approach to equilibrium.

Energy Dynamics improves on the bond model by adding an inductive element to represent the convection of the water and by using an accurate value for the thermal resistance. The improved model is shown in Figure 5.4.

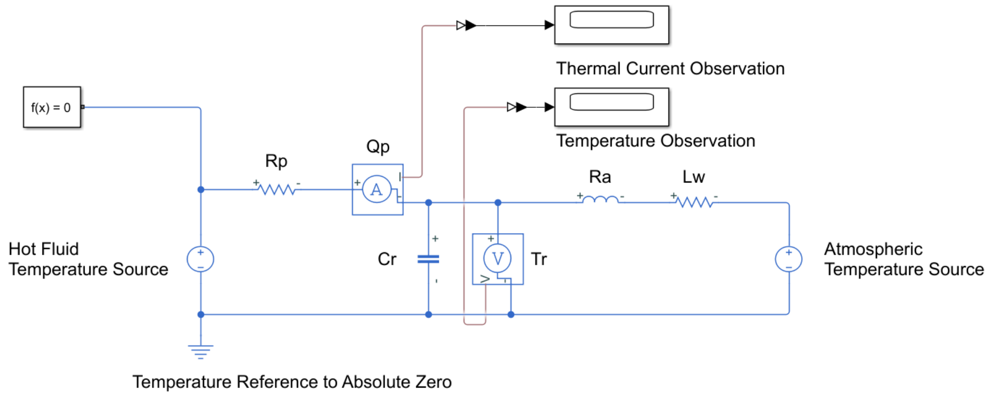

Figure 5.4 Improved Thermal Circuit

Simulating temperature versus time of the Energy Dynamics improved bond graph looks similar to the previous result. This similarity drops away as the inductance effect is increased. Once the system achieves an overdamped ratio, the temperature profile now becomes as shown in Figure 5.5.

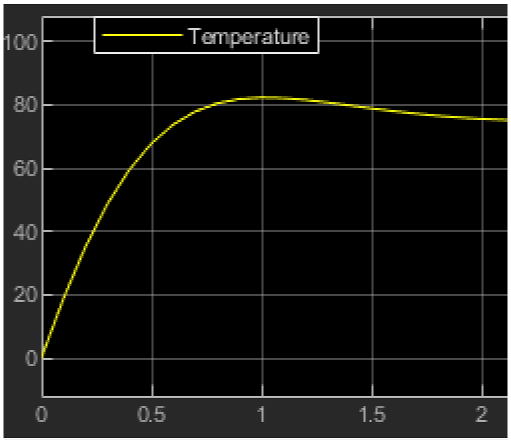

Figure 5.5 Temperature Profile of Advanced Model

In this final simulation we observe the effect of thermal inductance on the water temperature as predicted by Bosworth & Groden in their 1960 experiment. This is seen in the initial rise to a higher water temperature than the steady state temperature. Classical thermodynamics and bond graphs based on it fail to predict this initial overshoot in temperature.

These results demonstrate the capability that Energy-Dynamics provides in correcting the bond graph by utilizing corrected measurements for thermal resistance and accounting for thermal inductance.

5.2. *Carnot Efficiency*

"The efficiency of all reversible engines operating between the same two temperatures is the same, and no irreversible engine operating between these temperatures can have a greater efficiency than this" [25]. Stated mathematically,

$$Carnot\ Efficiency = \frac{T_H - T_C}{T_H} * 100\% \tag{61}$$

From the perspective of Energy Dynamics, the problem is simply one of two effort sources, one at a higher level than the other. From this some fluent is forced to flow. The flow of entropy from a temperature source will have some power output. The temperature source receiving the entropy being at a lower temperature will be receiving less power than the first source is putting out. The energy flow that is not received at the colder source is being converted into useful work. Energy Dynamics describes this conversion as shown in Figure 5.6 wherein,

$$P_{Converted\ Work} = T_H I_{th} - T_C I_{th} \tag{62}$$

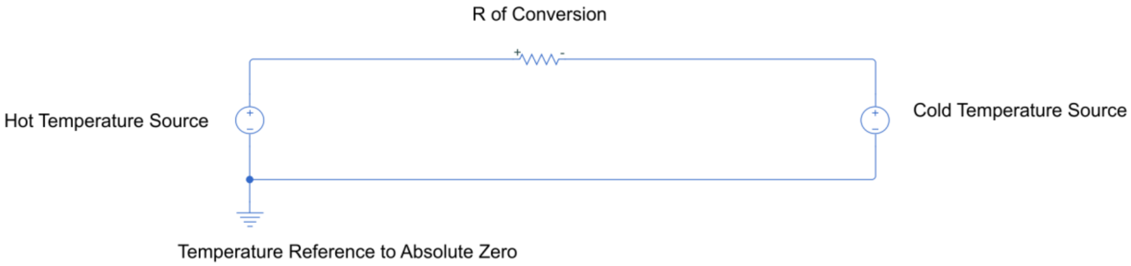

Figure 5.6 Carnot System

Because the thermal current, flow of entropy, is equal between the hot and cold source; it can be canceled out of the mathematical description. The Carnot Efficiency then is

$$Efficiency_{max} = \frac{T_H I_{th} - T_C I_{th}}{T_H I_{th}} = 1 - \frac{T_C}{T_H}. \tag{63}$$

If the temperature of the heat sink is absolute zero, then all of the power is recovered. Note that the exact same equations hold true for an electrical system (the architype domain) and the power efficiency thereof. This is expected, of course, as Energy-Dynamics theory hold all domains to behave similarly in regard to effort, flow, and energy transfer.

5.3. *Superconductivity*

Another unique application of Energy-Dynamics in the thermal domain is to provide a macroscopic description for superconductivity. Superconductivity is the drop of resistance in certain conductors to zero below a certain critical temperature. This resistance drop phenomenon is shown in Figure 5.7.

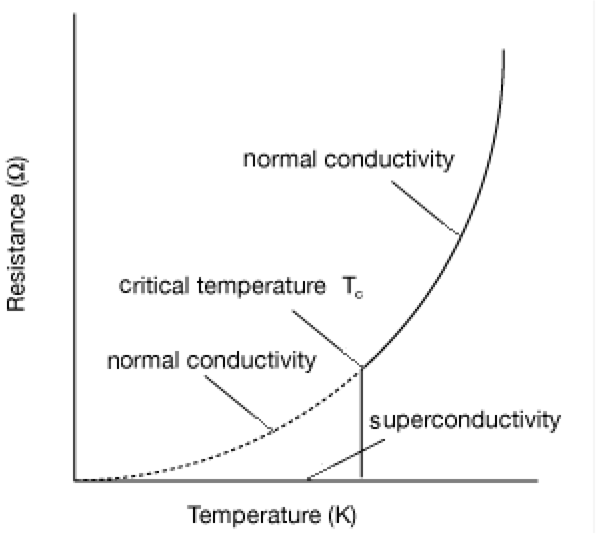

Figure 5.7 Resistance of Superconductor

This behavior is anticipated because as the material cools, its entropy becomes immobile and thermal flow approaches zero. Because thermal systems are a composite domain, the interplay between them and electrical systems is a gyration. The relationship mathematically then is seen through the following equations.

$$R_e = V_e / I_e \tag{64}$$

$$V_e = g * I_{th} \tag{65}$$

Substituting (64) into (65),

$$R_e = \frac{g * I_{th}}{I_e} \tag{66}$$

And thus as I_{th} approaches zero, R_e must also approach zero. When R_e is zero, then there is no power lost in an electrical circuit to I^2R inefficiency, and current travels un-impeded with no assistance.

Another variation to demonstrate the prediction of superconductivity through Energy Dynamics is to consider the gyration wherein,

$$\frac{1}{2} C_{th} T^2 = I_{electric}^2 R_{electric} t \tag{67}$$

Here we rearrange and solve for R as a function of the other variables to get:

$$R_{electric} = \frac{T^2 C_{th}}{2 I_{electric}^2 t} \tag{68}$$

From this we see that as T approaches zero, then $R_{electric}$ must also approach zero. Both of these derivations in (67) and (68) show that because the thermal domain is a composite domain coupled through gyration with the electrical domain, the effect of temperature going to zero is to also bring the electrical resistance to zero. These macroscopic predictions of Energy Dynamics have been demonstrated to be accurate and supported at the microscopic level by quantum physics. [27]

At the microscopic scale, this effect is due to the mode of current flow. When electrons travel through a conductor, they must travel through the atoms within the conductor in domino style. The electro voltaic potential on one end of the conductor is sufficient to force an electron off the nearest atom and on to the next one in the chain. This atom then also has an electron bumped off, and so on and so forth in such a manner that an electron appears to be flowing through the conductor. As these electrons move through the chain, they are constantly bumping into other atoms and particles which acts as an atomic level friction, agitating these other particles and taking energy away from the traveling electron as Cooper pairs are broken. The minimum amount of energy required to break an electron free from a Cooper pair is .001 eV. As per Boltzmann,

$$E = KT \tag{69}$$

Thus, when the temperature (T) is low enough, the electrons traveling and bumping into other atoms will not impart enough energy to break the bonds of Cooper pairs, and thus, no energy will be lost in the collisions. This can be thought of as a perfectly elastic collision in a Newton’s Cradle.

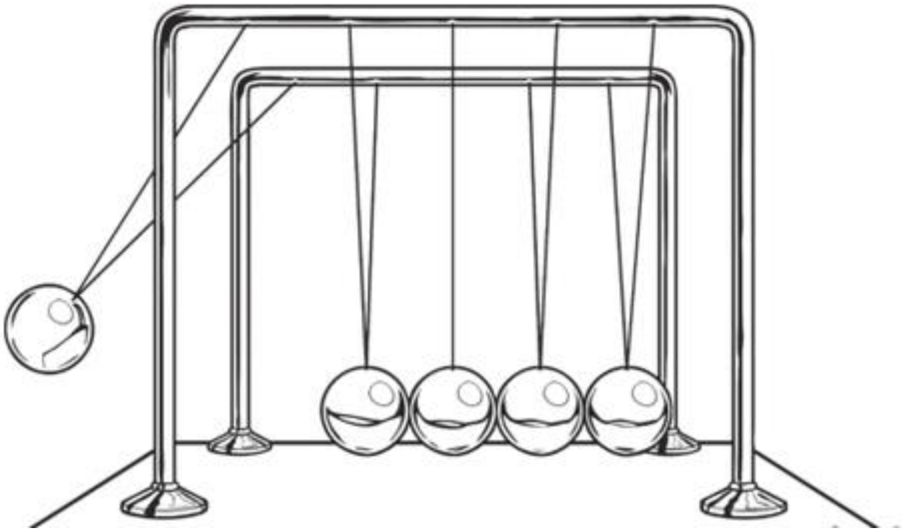

Figure 5.8 Newton's Cradle

A Newton’s Cradle, as shown in Figure 5.8, is an excellent example of superconductivity as it is clearly a composite domain through which energy moves. If the collisions are perfectly elastic on the Newton’s Cradle shown above, then the energy input on one side will transmit through with no loss to the far side. When the collisions are inelastic as in the case of normal temperature conduction, some of the energy will be lost to various things such as imperfections in the ball bearings, friction in the strings, air resistance, and so on. The end result is that the energy put in is dissipated into other domains such as thermal, acoustic, fluid dynamics of the air, and others outside the original mechanical domain in which it first entered.

6. CONCLUSIONS AND FUTURE WORK

6.1. Conclusions

The research discussed in this thesis utilized the concepts of Energy-Dynamics Theory, developed by Prof. Ehsani and his student, to address the thermal domain and develop a deeper understanding of the behavior of energy within it. While energy is purely an abstract mathematical bookkeeping concept, its applications add consistency and predictability to physical and engineering systems. In thermodynamic models, previous attempts at applying energy-related concepts such as bond graph analysis had made great progress by invoking the fundamental concepts of effort and flow. Our work, through the principles of analogy with the archetype domain of electro-magnetic, has defined a modeling methodology that more thoroughly explains the thermal domain, both theoretically and physically. In the process, new characteristic thermal constants of materials were defined that will have to be measured for the first time.

The laws of thermodynamics are given a solid foundation for the first time through Energy Dynamics theory and are consistent with mathematical expressions and ideas, reported in this thesis. This establishes the firm foundation of the Energy-Dynamics theory, consistent with the traditional thermodynamics. In addition, this thesis illustrates the previously stipulated concept of thermal inductance effects [14].

6.2. *Future Work*

Future developments of the work begun in this thesis can be the following:

1. Measuring and characterizing the thermal inductance effects of various materials
2. Cataloging the true thermal resistances of material using the newly developed definition of thermal resistance as given in (38)
3. Examining the utilization of thermo-plastics as switches in thermal circuit design, for background on these see [28] for a discussion of plastics that conduct in one axis but when rotated 90 degrees act as thermal insulators
4. Utilizing thermal diodes in developing complete thermal energy conversion devices such as Buck and Boost converters. See [29] for discussion of the existence of such a diode
5. Delving deeper into the analogs between the thermal domain and the wireless communication realm to leverage the fluent properties of information entropy
6. Measuring the new materials constant of thermal resistivity, permittivity and permeability of various materials.

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