**THERMODYNAMIC EXPOSE OF THE CONGRUENCY AND NON-CONGREUNCY OF HEAT-TEMPERATURE RELATION.**

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**Abstract**

The relationship between heat and temperature is fundamental to understanding the behavior of energy and matter in various physical systems. This thermodynamic expose examines the interplay between heat and temperature, exploring the congruency and non-congruency that underlie their association. In their congruence, the heat-temperature relation follows a straightforward path dictated by the heat capacity of the material. When a small amount of heat is added or removed, the resulting temperature change is proportional and reversible. This congruency holds for most common materials under specific conditions. However, the congruency principle begins to falter in systems that undergo phase transitions or exhibit anomalous behaviors, such as those near critical points.

Non-congruent systems challenge the simplicity of the heat-temperature relationship. Such systems exhibit phenomena like hysteresis, irreversible processes, and temperature changes that are disproportionate to the amount of heat transferred. Phase transitions, such as solid-to-liquid or liquid-to-gas transformations, introduce latent heat, causing temperature plateaus during heating or cooling. These non-congruent behaviors are essential to understanding phenomena like supercooling, superheating, and the operation of various heat engines and refrigeration cycles.

By examining the underlying thermodynamic principles, the nuanced mechanisms governing this relationship are shed to light on instances where congruency prevails and where it falters.

**Introduction**

The interplay between heat and temperature lies at the heart of the detailed physical interactions that govern the behavior of matter. The study of thermodynamics unravels the underlying principles that dictate how thermal energy flows and transforms within a system. A pivotal aspect of this study is the exploration of the congruency and non-congruency of the heat-temperature relationship – a dynamic interplay that governs the response of materials to thermal energy input and reveals the fascinating complexities that arise in diverse physical and chemical processes.

At its essence, the heat-temperature relationship encapsulates the fundamental connection between the energy added to a system in the form of heat and the resulting change in its temperature. When this relationship is congruent, it adheres to a linear and predictable pattern, where incremental additions or subtractions of heat lead to proportional and reversible temperature changes. Such behavior, observed in many everyday scenarios, forms the bedrock of our understanding of thermal equilibrium and heat capacity.

However, as the study goes deeper, a tapestry of non-congruencies unfurls. Certain systems challenge the straightforward heat-temperature relationship, exhibiting intricate behaviors that defy simple expectations. These non-congruencies encompass phase transitions, critical points, and exotic phenomena that encompass hysteresis, latent heat, and irreversible changes in temperature. Such behavior is not only of fundamental scientific interest but also has critical implications for practical applications, from the operation of engines and refrigeration systems to the behavior of materials under extreme conditions.

**Background and Concepts**

**The Concept of Heat**

Heat is a form of energy transferred between two systems or a system and its surroundings due to a temperature difference. It is usually represented by Q and is expressed in joule (J) or kilo-joule (kJ). It is a key concept that plays a central role in understanding the behavior of matter and energy in various physical processes. Heat transfer is essential for explaining how energy flows and is exchanged in different systems, and it is closely related to changes in temperature.

**Transfer of Energy**: Heat transfer occurs when there is a temperature difference between two systems. Heat flows from a region of higher temperature to a region of lower temperature. The Second Law of Thermodynamics determines the direction of heat transfer, which states that heat naturally flows in the direction of increasing entropy, or disorder.

**Specific Heat**: The specific heat capacity of a substance is the amount of heat required to raise the temperature of a unit mass of the substance by one degree. It is generally denoted by c. In the S.I. system of units, the unit of specific heat (c) is taken as KJ/kgK. If m kg of a substance of specific heat c is required to raise the temperature from an initial temperature of T1 to a final temperature of T2, then

Heat required = mc(T2 –T1) kJ

Where T1 and T2 may be in C or K.

Different substances have different specific heat capacities, and this property is important in determining how substances respond to changes in temperature.

**Heat Transfer Mechanisms**: Heat can be transferred through three main mechanisms:

**Conduction**: Transfer of heat through direct contact between particles of a substance without the actual movement of the particles. Conduction occurs when there is a temperature gradient within a solid material, causing higher kinetic energy (temperature) molecules to transfer their energy to lower kinetic energy molecules.

The rate of heat conduction is governed by Fourier's Law of Heat Conduction, which states that the heat flux (amount of heat transferred per unit area and time) is proportional to the negative of the temperature gradient:

q=−k⋅A⋅dx/dT

Where:

q is the heat flux (W/m²),

k is the material's thermal conductivity (W/m·K),

A is the cross-sectional area perpendicular to the heat flow (m²),

dx/dT​ is the temperature gradient in the direction of heat transfer (K/m).

**Convection**: Transfer of heat through the movement of fluid (liquid or gas) caused by density differences due to temperature variations. The convective Heat Transfer Coefficient (h) represents the effectiveness of heat transfer between a solid surface and a moving fluid. It depends on factors such as fluid properties, flow velocity, and the geometry of the solid surface. The convective heat transfer rate (Q=h⋅A⋅ΔT) is proportional to the difference in temperature (ΔT) between the solid surface and the fluid.

The rate equation for the convective heat transfer (regardless of particular nature) between a surface and an adjacent fluid is prescribed by Newton’s law of cooling

Q = hA(ts – tf)

where, Q = Rate of conductive heat transfer,

A = Area exposed to heat transfer,

ts = Surface temperature,

tf = Fluid temperature, and

h = Co-efficient of conductive heat transfer.

The units of h are W/m2°C or W/m2K

**Radiation**: Transfer of heat through electromagnetic waves, such as infrared radiation. Unlike conduction and convection, radiation doesn't require a medium for energy transfer. The contribution of radiation to heat transfer is very significant at high absolute temperature levels such as those prevailing in furnaces, combustion chambers, nuclear explosions, and in space applications. Thermal radiations exhibit characteristics similar to those of visible light and follow optical laws. These can be reflected, refracted and are subject to scattering and absorption when they pass through a media. They get polarized and weakened in strength with the inverse square of radial distance from the radiating surface.

**Calorimetry**: Calorimetry is the experimental measurement of heat changes during chemical reactions or physical processes. Calorimeters are devices designed to measure the heat exchange between a system and its surroundings.

**Heat, Internal Energy, and First Law of Thermodynamics**: Heat is related to the internal energy of a system. Internal energy includes both the kinetic energy of the particles within a system and the potential energy due to their interactions. Heat added to a system increases its internal energy, which in turn can result in a change in temperature or a change of state. **Internal energy** is the sum of the kinetic and potential energies of a system’s atoms and molecules. It can be divided into many subcategories, such as thermal and chemical energy, and depends only on the state of a system (that is, *P*,*V*, and *T*), not on how the energy enters or leaves the system.

The First Law, also known as the Law of Conservation of Energy, states that when a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to the network done by the system on its surroundings. In the context of heat, the First Law explains that the energy transferred as heat to a system is used either to do work or to increase the internal energy of the system.

When a process is executed by a system, the change in stored energy of the system is numerically equal to the net heat interactions minus the network interaction during the process.

∴ E2 – E1 = Q – W

∴ ΔE = Q – W [or Q = Δ E + W]

Δ E = E2 – E1

where E represents the total internal energy.

**The Concept of Temperature**

Temperature is an intensive thermodynamic property, which determines the degree of hotness or the level of heat intensity of a body. It is often measured using different scales, such as Celsius (°C) or Fahrenheit (°F), but in thermodynamics, the Kelvin (K) scale is the most commonly used. The Kelvin scale is an absolute temperature scale where zero Kelvin (0 K) is referred to as absolute zero, the point at which all thermal motion ceases. Absolute zero is equivalent to approximately -273.15°C or -459.67°F.

The concept of temperature is closely related to the behavior of particles at the molecular level. In simple terms, temperature reflects how fast the particles in a substance are moving. When particles have higher kinetic energy (they move faster), the substance's temperature is higher, and conversely, when particles have lower kinetic energy (they move slower), the temperature is lower.

**Zeroth Law of Thermodynamics**: This law states that if two systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other. In other words, if A and B are in thermal equilibrium with C, then A and B are also in thermal equilibrium with each other. This law provides the basis for temperature measurement.

**Absolute Zero:** Absolute zero is the lowest possible temperature, where the kinetic energy of particles theoretically becomes zero. It corresponds to 0 Kelvin (0 K), -273.15°C, or -459.67°F.

**Thermal Equilibrium**: When two systems are at the same temperature and no net heat flows between them, they are in thermal equilibrium. This forms the basis for temperature measurement. In thermal equilibrium, there is no temperature gradient or difference between the objects, so there is no tendency for heat to flow from one to the other.

**Heat Transfer**: Heat naturally flows from a region of higher temperature to a region of lower temperature. The rate of heat transfer depends on the temperature difference between the two regions.

**Thermal Expansion**: Thermal expansion refers to the tendency of materials to change their dimensions, such as length, volume, or area, in response to changes in temperature. Most substances expand when heated and contract when cooled. This is due to the increased kinetic energy of particles at higher temperatures, which causes them to move farther apart.

**Thermal Conduction:** The rate of heat conduction through a material depends on the temperature gradient (difference in temperature) across the material. Heat flows from regions of higher temperature to regions of lower temperature.

**Thermodynamic Processes**: Temperature changes are integral to various thermodynamic processes, including isothermal (constant temperature), adiabatic (no heat exchange), and isobaric (constant pressure) processes.

**Ideal Gas Law**: In the context of ideal gases, the pressure, volume, and temperature are related through the ideal gas law: PV = nRT, where P is pressure, V is volume, n is the number of moles of gas, R is the gas constant, and T is the temperature in Kelvin.

**Heat-Temperature Relation**

Heat and temperature are related, but they are not the same. The amount of heat transferred between objects depends on the temperature difference between them, the thermal properties of the materials, and the time over which the transfer occurs. In other words, temperature difference drives the flow of heat. When the two systems are in contact, heat will be transferred through molecular collisions from the hotter system to the cooler system. The thermal energy will flow in that direction until the two objects are at the same temperature. When the two systems in contact are at the same temperature, we say they are in thermal equilibrium. The impact of heat on a body is its temperature. In other words, heat causes temperature.

On an atomic level, the molecules in each object are constantly in motion and colliding with each other. Every time molecules collide, kinetic energy can be transferred. When the two systems are in contact, heat will be transferred through molecular collisions from the hotter system to the cooler system. The thermal energy will flow in that direction until the two objects are at the same temperature, thus being in thermal equilibrium.

**Heat Transfer and Temperature Difference**: Heat transfer occurs between two objects when they have different temperatures. Heat flows naturally from an object at a higher temperature to an object at a lower temperature. The greater the temperature difference between the objects, the more heat is transferred.

**Temperature Change**: When heat is added or removed from a substance, its temperature changes. This relationship is described by the heat capacity or specific heat capacity of the substance. Heat capacity (C) is the amount of heat required to raise the temperature of a substance by a certain amount. Specific heat capacity (c) has been defined earlier to mean the heat required to raise the temperature of a unit mass of a substance by a certain amount.

Mathematically, the relationship can be expressed as: Q = mcΔT Where:

Q is the heat transferred

m is the mass of the substance

c is the specific heat capacity of the substance

ΔT is the change in temperature

The equation indicates that the amount of heat transferred is directly proportional to the mass of the substance and the change in temperature, and it also depends on the specific heat capacity of the substance. Different substances have different specific heat capacities, which means they require different amounts of heat to achieve the same temperature change. It's important to note that the heat-temperature relationship assumes that the substance undergoes no phase changes (e.g., melting, boiling) during the heating or cooling process.

Note that when the temperature increases, Q and ΔT are taken to be positive, and energy transfers into the system. When the temperature decreases, Q and ΔT are negative, and energy transfers out of the system. Speciﬁc heat varies with temperature. However, if temperature intervals are not too great, the temperature variation can be ignored and c can be treated as a constant. For example, the speciﬁc heat of water varies by only about 1% from 0°C to 100°C at atmospheric pressure. Unless stated otherwise, we shall neglect such variations. Measured values of speciﬁc heats are found to depend on the conditions of the experiment. In general, measurements made in a constant-pressure process are different from those made in a constant-volume process. For solids and liquids, the difference between the two values is usually no greater than a few percent and is often neglected.

The heat-temperature relation is not linear. This means that the amount of heat required to raise the temperature of a substance by a certain amount increases as the temperature increases. This relation is reversible. This means that the same amount of heat that is used to raise the temperature of a substance can also be used to lower its temperature. The heat-temperature relation is applicable to all substances, but the specific heat of each substance is different.

**Second Law of Thermodynamics and Entropy**

According to Clausius, ‘It is impossible for a self-acting machine working in a cyclic process, unaided by any external agency, to convey heat from a body at a lower temperature to a body at a higher temperature.’ This relies on the concept of entropy, which is a measure of disorder in a system. Entropy is a function of a quantity of heat which shows the possibility of conversion of that heat into work. The increase in entropy is small when heat is added at a high temperature and is greater when heat addition is made at a lower temperature.

The equation for the change in entropy, ΔS, is

ΔS=Q/T,

where *Q* is the heat that transfers energy during a process, and *T*is the absolute temperature at which the process takes place. Q is positive for energy transferred into the system by heat and negative for energy transferred out of the system by heat. In SI, entropy is expressed in units of joules per kelvin (J/K).

**Congruency of Heat-Temperature Relation**

The congruency of the heat-temperature relationship can be observed when heat flows from a system at a higher temperature to a system at a lower temperature. This is in line with the second law of thermodynamics, which states that heat always moves from a body of higher temperature to a body of lower temperature due to the fundamental principle of increasing entropy.

The congruency of the heat-temperature relation refers to the fact that heat transfer between two objects or systems is solely determined by the temperature difference between them, assuming that other factors such as material properties, geometry, and thermal conductivity remain constant. The transfer of heat occurs due to a temperature difference between two systems, and the laws of thermodynamics provide the framework for understanding and predicting how heat and temperature behave in various situations.

**The Ideal Gas Law**

In ideal gas systems, the relationship between heat and temperature is congruent when the conditions remain constant. According to the ideal gas law (PV = nRT), where P is pressure, V is volume, n is the number of moles, R is the ideal gas constant, and T is temperature, an increase in temperature under constant pressure leads to an expansion of the gas volume. Temperature changes can result in changes in pressure and volume, and these changes can be associated with heat transfer.

**Calorimetry**: In calorimetric experiments, where the heat transfer is isolated from the surroundings, the change in temperature of a substance is directly proportional to the heat added or removed.

**Specific Heat Capacity**: The specific heat capacity of a substance is the amount of heat required to raise the temperature of a unit mass of that substance by one degree Celsius (or one Kelvin). The temperature change and the heat added or removed are directly related to the specific heat capacity.

**Latent Heat of Phase Transitions**

During phase transitions, such as melting and vaporization, the temperature remains constant even as heat is added. This phenomenon, known as latent heat, exemplifies the congruent behavior of heat and temperature during these transitions.

**Non-Congruency of Heat-Temperature Relation**

The non-congruency of the heat-temperature relationship arises when considering situations where there is a change in phase or during a phase change process. During phase changes, such as the condensation process, the energy equation involving temperature and the thermodynamic relation of entropy become important. The condensation process requires the consideration of both the fluid flow model and the energy equation involving temperature. The fluid flow model provides insights into the macroscopic variables of volume, pressure, and temperature, while the energy equation involving temperature accounts for the specific heat at constant volume (c\_v) and the thermal conductivity (λ).

Although heat and temperature are related in terms of energy transfer and the effect of temperature on the amount of heat transferred, they are distinct concepts. Temperature represents the intensity of thermal energy, while heat is the energy transferred due to a temperature difference.

**Specific Heat**

Different substances have varying abilities to absorb heat without a proportional increase in temperature. This property is captured by the concept of specific heat. Non-congruency is evident when substances with different specific heats experience different temperature changes despite receiving the same amount of heat.

**Phase Change and Latent Heat**

A substance often undergoes a change in temperature when energy is transferred between it and its surroundings. There are situations, however, in which the transfer of energy does not result in a change in temperature. This is the case whenever the physical characteristics of the substance change from one form to another; such a change is commonly referred to as a phase change. Two common phase changes are from solid to liquid (melting) and from liquid to gas (boiling); another is a change in the crystalline structure of a solid. All such phase changes involve a change in internal energy but no change in temperature. The increase in internal energy in boiling, for example, is represented by the breaking of bonds between molecules in the liquid state; this bond breaking allows the molecules to move farther apart in the gaseous state, with a corresponding increase in intermolecular potential energy.

The energy required to change the phase of a pure substance of mass

m is Q = mL

 where L is the latent heat of the substance and depends on the nature of the phase change and the properties of the substance.

When a gas cools, it eventually condenses and returns to the liquid phase. The energy given up per unit mass is called the latent heat of condensation and is numerically equal to the latent heat of vaporization. Likewise, when a liquid cools, it eventually solidiﬁes, and the latent heat of solidiﬁcation is numerically equal to the latent heat of fusion.

When heat is added or removed during a change of state (e.g., solid to liquid), the temperature remains constant until the entire substance has undergone the transition. This non-congruency illustrates that temperature alone is insufficient to predict the heat absorbed or released during such processes.

Other aspects where heat is quite different from temperature are in:

**Definition**: Heat is the energy transferred between systems due to a temperature difference. It flows from a region of higher temperature to a region of lower temperature. Temperature, on the other hand, is a scalar quantity that quantifies the thermal state of a system and reflects the average kinetic energy of its particles.

**Units**: Heat is typically measured in units like joules (J) or calories (cal), while temperature is measured in degrees Celsius (°C) or Kelvin (K).

**State vs. Process**: Temperature is a state variable, meaning it describes the current condition of a system and remains constant in a reversible process. Heat, however, is a process variable that describes the energy transfer between two systems during a specific process.

**Energy Conservation**: In the context of energy conservation, heat is part of the energy that enters or leaves a system, contributing to changes in its internal energy or performing work. Temperature, however, is a property that characterizes the thermal state of a system and is not directly associated with energy conservation.

**Change vs. Property**: Temperature represents a property of a system, indicating how hot or cold it is. Heat, on the other hand, represents a change in energy, specifically the transfer of thermal energy from one place to another.

**Applications and Examples**

**Thermal Comfort and HVAC Design**: In designing heating, ventilation, and air conditioning (HVAC) systems for buildings, understanding the relationship between heat and temperature is crucial. Maintaining a comfortable indoor temperature requires regulating the heat transfer between indoor and outdoor environments.

**Thermal Expansion**: As substances are heated, their particles gain kinetic energy, leading to increased movement. This movement causes the substance to expand. This principle is used in various applications, such as designing bridges, railways, and pipelines to accommodate expansion and contraction due to temperature changes.

**Thermometers**: Temperature measurement devices, such as mercury or digital thermometers, rely on the expansion and contraction of materials (e.g., mercury, liquid crystals) in response to temperature changes.

**Thermal Imaging**: Infrared cameras use the heat-temperature relationship to create images based on the infrared radiation emitted by objects. This technology has applications in fields like building inspection, electrical troubleshooting, and medical imaging.

**Cryogenics**: In cryogenic applications, extremely low temperatures are achieved by carefully managing the transfer of heat. For example, superconductors exhibit their unique properties at extremely low temperatures.

**Heat Engines and Thermodynamics**: The efficiency of heat engines, such as car engines or power plants, relies on the heat-temperature relationship. The Carnot efficiency, a fundamental limit for heat engines, is determined by the temperature difference between the hot and cold reservoirs.

**Cooking**: In culinary applications, understanding the heat-temperature relationship is essential. Different cooking methods involve controlling the heat applied to food to achieve specific temperatures and desired levels of doneness.

**Heat Treatment of Materials**: When heat-treating materials such as metals, the congruency of the heat-temperature relation is significant. Different materials respond differently to heating and cooling cycles, even if the temperatures are the same. Factors like the material's specific heat capacity, thermal conductivity, and phase transitions all impact the outcome of the heat treatment process.

**Thermal Conductivity Measurement**: The heat-temperature relationship is used to determine the thermal conductivity of materials, which is essential in fields like building insulation design and material engineering.

**Climate Science**: Understanding how heat is transferred and distributed in Earth's atmosphere and oceans is crucial for studying climate patterns and making climate predictions.

**Medicine**: In medical applications, understanding the heat-temperature relationship is important for monitoring body temperature, assessing fever, and conducting various medical procedures.

**Environmental Monitoring**: Temperature changes can affect ecosystems and natural habitats. Monitoring temperature variations in bodies of water, soil, and air is important for environmental research and conservation efforts.

**Heat Transfer with Phase Change**: When a substance undergoes a phase change, such as solid to liquid or liquid to gas, the heat-temperature relation is non-congruent. During phase changes, the temperature of a substance remains constant even though heat is being added or removed. This is evident during processes like melting and boiling, where the added heat energy is used to change the substance's phase rather than increase its temperature.

**Conclusion**

The congruency and non-congruency of heat-temperature relations are fundamental to comprehending energy transfer, equilibrium, and the behavior of matter in various contexts. This paper has examined these concepts, highlighting scenarios where their relationship aligns and where it deviates. While congruency holds in many scenarios, the non-congruent instances shed light on the deeper intricacies governing heat transfer and phase transitions.

Understanding the heat-temperature relation is very key to solving thermodynamic problems and very essential in the design of various components especially HVAC systems.

**References**

Kotz, J. C., Treichel, P. M., Townsend, J. R., and Treichel, D. A. Specific Heat Capacity: Heating and Cooling. In Chemistry and Chemical Reactivity, Instructor's Edition (9th ed., pp. 184-189). Stamford, CT: Cengage Learning; 2015.

Rajput, R. K. Thermal Engineering. New Delhi: Laxmi Publications; 2017.

Khurmi R. S., Gupta J. K. A Textbook of Thermal Engineering. New Delhi: S Chand & Company; 2010.

Cengel YA, Boles MA. Thermodynamics: An Engineering Approach. 5th ed. Boston: McGraw-Hill College; 2006.

Andresen B, Salamon P, Berry RS. Thermodynamics in finite time: extremals for imperfect heat engines. The Journal of Chemical Physics. 1976;66(4):1571–1576.

Sonntag RE, Van Wylen GJ. Introduction to Thermodynamics. 3rd ed. New York: Wiley; 1991. 800 p.

Chen LG, Wu C, Sun FR. Finite time thermodynamic optimization or entropy generation minimization of energy systems. J Non-Equilib Thermodyn. 1999;24(4):327–359.