

Recent Trends and Applications of Non-Equilibrium Thermodynamics

Dr. Sailesh Kumar Singh

Associate Professor, Department of Mechanical Engineering, Dronacharya Group of Institutions, Greater Noida, Uttar Pradesh

shailesh.singh@gnindia.dronacharya.info

Mr. Vishnu Kuntal

Assistant Professor, Department of Mechanical Engineering, Dronacharya Group of Institutions, Greater Noida, Uttar Pradesh

vishnu.kuntal@gnindia.dronacharya.info

Abstract

The rapidly developing field of non-equilibrium thermodynamics applies the concepts of classical thermodynamics to systems that are far from equilibrium. The most recent theoretical advancements, such as quantum thermodynamics, stochastic thermodynamics, and the thermodynamics of information, are examined in this work. Additionally, it looks at a variety of applications in environmental science, energy systems, biology, and nanotechnology. In addition to expanding our knowledge of intricate systems, these developments spur innovation in advanced materials, sustainable energy, and medical diagnostics. The paper presents a model of a diffusive universe consisting of diffusive barotropic fluids, analyzing thermodynamic stability for both constant and variable barotropic index fluids. It discusses the acceptability of the dark energy hypothesis from a thermodynamic point of view. The paper investigates the possibility of an emergent scenario in a single fluid diffusive Universe, incorporating the diffusion mechanism in Einstein's field equation. It also presents a successful exhibition of complete and continuous cosmic evolution from the emergent era to the present late time acceleration phase. The paper also introduces a cyclic universe, a system undergoing cyclic thermodynamic processes, introducing the evolution of a cosmic heat engine. Future work may explore different models of the Universe in the context of diffusive fluid systems.

Keywords: - Stochastic Thermodynamics, Entropy Production, Quantum Thermodynamics, Energy Conversion.

Introduction

Thermodynamics is a subfield of physics that studies how heat in a system can transform into various forms of energy, particularly mechanical work. It focuses on the relationship between heat, electrical agency, and forces between body parts. The laws of thermodynamics specify whether a system's energy change can have a beneficial effect on its surroundings. The universe is made up of a system and its surroundings, with boundaries categorized into three types: permeable, diathermal, and adiabatic. The four laws of thermodynamics are thermal equilibrium, conservation of energy, joule's equivalency principle, heat engine principle, refrigerator principle, and changes in chaosness of a system due to interaction with heat and work. This paper discusses the cyclic evolution of a diffusive universe, a phenomenological approach to model a cosmic heat engine. Bulk flow, or advection, refers to the motion of an entire substance from or to a system due to pressure gradients. Diffusion, on the other hand, is the gradual transport or dispersion of concentration within a body due to concentration gradients. Inhomogeneity of concentration within the system leads to disturbance in the equilibrium condition, causing a pressure called 'diffusive pressure' to drive the flow of

10.48047/jocaaa.2024.33.02.35

molecules. Both advection and diffusion processes are thermodynamically irreversible processes. The cosmic diffusion mechanism can be considered as the diffusion of a cosmic fluid within a continuously evolving isolated system. The Universe is assumed to be an isolated system of diffusive barotropic fluid with a constant equation of state parameter (ω). The particle creation-annihilation process creates a concentration gradient within the system, leading to diffusive pressure (P). The energy-momentum tensor of a diffusive fluid is not covariantly conserved, violating the Bianchi identity of the Einstein field equations. To incorporate the diffusive fluid in the matter component of GTR, an extra matter component is chosen as a form of a time-dependent cosmological scalar field (ϕ). This scalar field acts as a matter creation-annihilation field, causing a bulk flow mechanism that drives the cosmic fluid into diffusion [1-5].

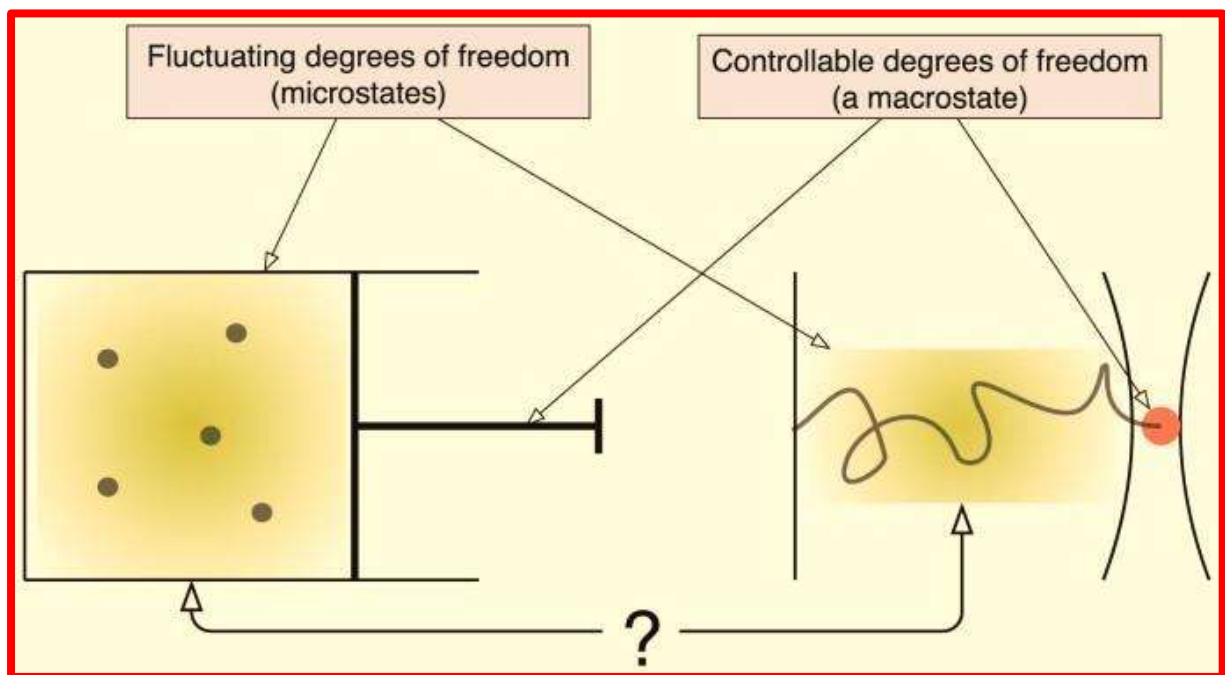


Fig.-1 Basic concept

The modified Einstein field equations are identical with the normal field equation with a varying cosmological constant (Λ), replacing Λ with a time-dependent scalar field ϕ . The modified Friedmann equations with diffusion dynamics take the form $3H^2 = \rho + \phi$. The matter conservation equation for the matter field takes the form $\rho' + 3H(\rho + p) = \sigma_0 a^{-3} = \sigma_0 a^{-3}$. The cosmological scalar field is the negative dissipative pressure in effective Einstein gravity [6-10].

The evolution of the instantaneous equilibrium temperature (T) is governed by the equation $T'T + \partial P \partial \rho (3H - |\Gamma\phi|) = 0$. The matter creation mechanism involves change in Gibbs free energy (G) of a system. The first law of thermodynamics states that any system interacting with thermal energy converts a fraction of heat into the corresponding amount of work, i.e., any thermodynamic system has the heat engine property with efficiency $\eta < 1$. The cosmic heat engine follows a cyclic and bouncing evolution pattern, with the cyclic stage

being the emergent stage. In a bouncing universe, the dependence of ϕ on H up to second order is considered [11-15].

The cyclic evolution of a diffusive Universe can be modelled using a phenomenological approach. The energy density at the emergent epoch is determined by a negative constant, α . The equation for the evolution can be written as $2H' + 4\beta(1 - b_0a) + b_0a|t - \tilde{t}|H = 0$. The deceleration parameter is found as $q = a - b_0$, indicating that within the epoch range $\tilde{t} - \sqrt{1+2\beta} \leq t \leq \tilde{t} + \sqrt{1+2\beta}$, deceleration occurs, while acceleration occurs beyond this range. The other thermodynamic parameters are $\rho = 3H^2 - \phi = 4\beta(1 + \omega - b_0a + b_0a|t - \tilde{t}|)H$. The variation of different physical parameters, such as energy density ρ and temperature T . The cyclic evolution of a diffusive universe follows a valid thermodynamic cyclic process, except when ω is less than 0. The cosmological parameters, such as scale factor (a), Hubble parameter (H), and acceleration (\ddot{a}), as well as thermodynamic parameters like temperature (T) and energy density (ρ), are shown graphically in Figure 5.1 and Figure 5.2 for various parameter choices. The universe is in an emergent scenario in the infinite past, then expands and reaches a maximum, then contracts and enters an emergent scenario again. The Hubble parameter has zero values in the emergent phase, then undergoes increasing \rightarrow decreasing \rightarrow increasing behavior before approaching zero in the future emergent phase. The acceleration is zero in both the emergent phases and has positive \rightarrow negative \rightarrow positive values between the two asymptotic emergent epochs. The thermodynamic parameters, energy density (ρ) and temperature (T), show similar behavior with the evolution of the Universe. The present singularity free model of the Universe with diffusive fluid is interesting both from a cosmological and thermodynamic point of view. The model may be considered a cyclic model of the Universe if a wormhole connects the two asymptotic emergent phases. From a thermodynamic point of view, the model may be considered a non-equilibrium cyclic thermodynamic process and has some analogy with a heat engine [16-19].

Research Methodology

Non-Equilibrium Thermodynamics (NET) is a field that bridges statistical mechanics with thermodynamic quantities at the microscopic scale, accounting for thermal fluctuations and probabilistic behavior in small systems. It includes stochastic thermodynamics, the thermodynamics of information, quantum thermodynamics, and non-equilibrium phase transitions. NET is used in various applications, including cellular energy cycles, nanotechnology and material science, energy conversion and storage, environmental and atmospheric science, and soft matter and complex fluids. It also helps in understanding global energy balance, atmospheric dynamics, and entropy flows, which are critical in climate change modeling and meteorology. NET research also leverages computational tools like molecular dynamics, Monte Carlo simulations, and lattice Boltzmann methods. Challenges and future directions include integrating scales, designing experiments to measure entropy production and thermodynamic forces, expanding NET frameworks to economics, social sciences, and artificial intelligence, and promoting sustainability in renewable energy systems.

Result Analysis

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The standard cosmology is struggling to estimate the theoretical explanation for the recent observational evidence of the Universe's accelerated expansion. The cosmological constant is the best model supporting observational data, but it suffers from two serious problems. The inflationary scenario is a well-accepted theory of cosmic evolution just after the big-bang, but there are few cosmological models that describe the evolution of the Universe starting from the inflationary era to present late time acceleration or non-singular model starting from the Emergent or Bouncing Universe. This work is an example of such a cosmic model with cosmic fluid as diffusive barotropic fluid. The diffusion mechanism of a fluid is a dissipative phenomenon in non-equilibrium thermodynamics, with the diffusion force acting along the matter flow. The space time geometry is chosen as the maximally symmetric flat FLRW model, and the modified Einstein field equations are $3H^2 = \rho + \phi$, $2H' = -(\rho + p)$. The cosmological scalar field ϕ satisfies the evolution equation $\phi' + 3H\phi = 3\sigma_0 a^{-3}$. The particle creation/annihilation rate can be modified as $n' + 3Hn = n\Gamma_d$, and the temperature of the cosmic fluid can be determined as $T' + \omega(3H - \Gamma_d)T = 0$. The explicit solution for the emergent scenario should be in the form $H(E) = \eta E H_0 + (\eta E - H_0)e^{-3\eta E(1+\omega)(t-t_0)}$.

The study investigates the continuous cosmic evolution of cosmic fluids, focusing on thermodynamic parameters like energy density and temperature. It presents scale factor values for inflation to decelerated expansion and decelerated expansion phase to late time acceleration. The Hubble parameter and different thermodynamic parameters are also discussed. The deceleration parameter q is continuous near a_1 but not continuous at a_3 . The transition from deceleration to late time acceleration occurs later from a_3 , and the shift of transition epoch depends on the value of ω . The study also examines the variation of free energies, particularly Gibbs free energy, at transition epochs of evolution. The first order thermodynamic phase transition of cosmic fluid in continuous and complete cosmic evolution with diffusive barotropic fluid is discussed. The latent heat of the transition from the i -th phase to the j -th phase in cosmic evolution with diffusive barotropic fluid is variable in isobaric conditions, but without an isobaric constraint on the universe, the variation of ω with expansion can be neglected. The study successfully establishes the unified cosmic evolution under diffusion process, revealing that the thermodynamic phase transition of the diffusive cosmic fluid is of first order.

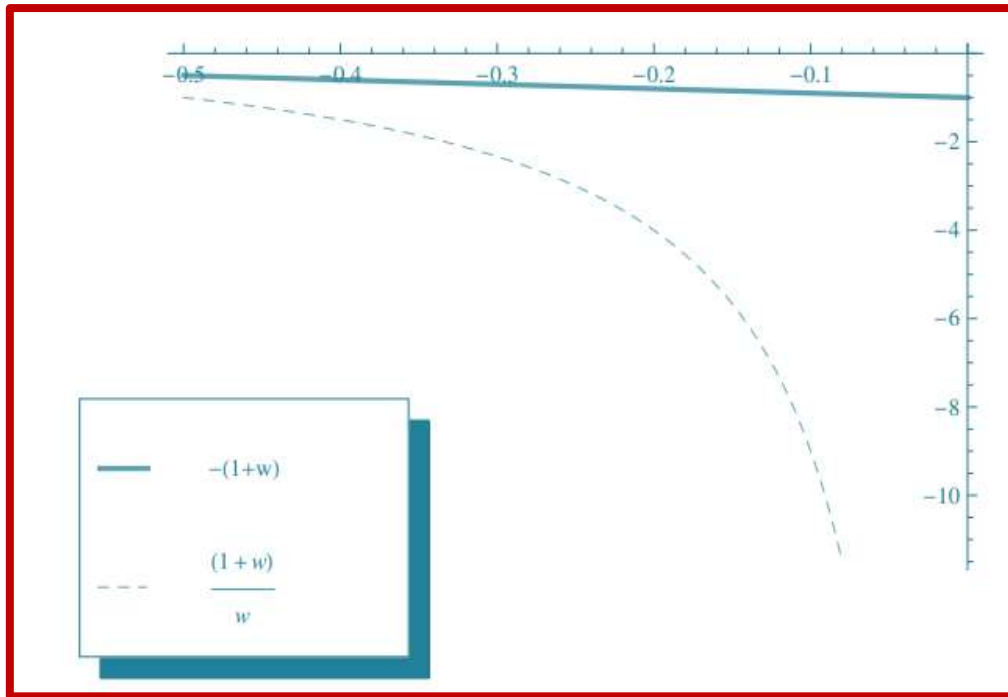


Fig.-2 Stability region

Table-1 Conditions for Stability for constant equation of state parameter fluids

range of ω_i	Stability Condition
$\omega_i \geq 0$	$\left[\frac{\partial \left\{ \ln \left(1 + \frac{\gamma_i}{\rho_{i0}} A_i \right) \right\}}{\partial \ln T} \right]_{p_i} \geq \frac{1 + \omega_i}{\omega_i}$
$-1 \leq \omega_i \leq 0$	$-(1 + \omega_i) \leq \left[\frac{\partial \left\{ \ln \left(1 + \frac{\gamma_i}{\rho_{i0}} A_i \right) \right\}}{\partial \ln T} \right]_{p_i}$ and $\left[\frac{\partial \left\{ \ln \left(1 + \frac{\gamma_i}{\rho_{i0}} A_i \right) \right\}}{\partial \ln T} \right]_{p_i} \leq \frac{1 + \omega_i}{\omega_i}$ simultaneously, which is not possible hence unstable.
$-2 \leq \omega_i \leq -1$	Unstable .
$\omega_i \leq -2$	$\left[\frac{\partial \left\{ \ln \left(1 + \frac{\gamma_i}{\rho_{i0}} A_i \right) \right\}}{\partial \ln T} \right]_{p_i} \geq -(1 + \omega_i)$

This study investigates the possibility of an emergent universe scenario under diffusion processes. A cosmological scalar field is chosen linearly to the Hubble parameter, resulting in variations in scale factor and equation of state parameters. The study also determines thermodynamic parameters like energy density and temperature under this scenario. The results show that dissipative processes like diffusion and particle creation may correspond to the universe's evolution pattern. Future work may explore the Lagrangian formulation of this non-equilibrium thermodynamic.

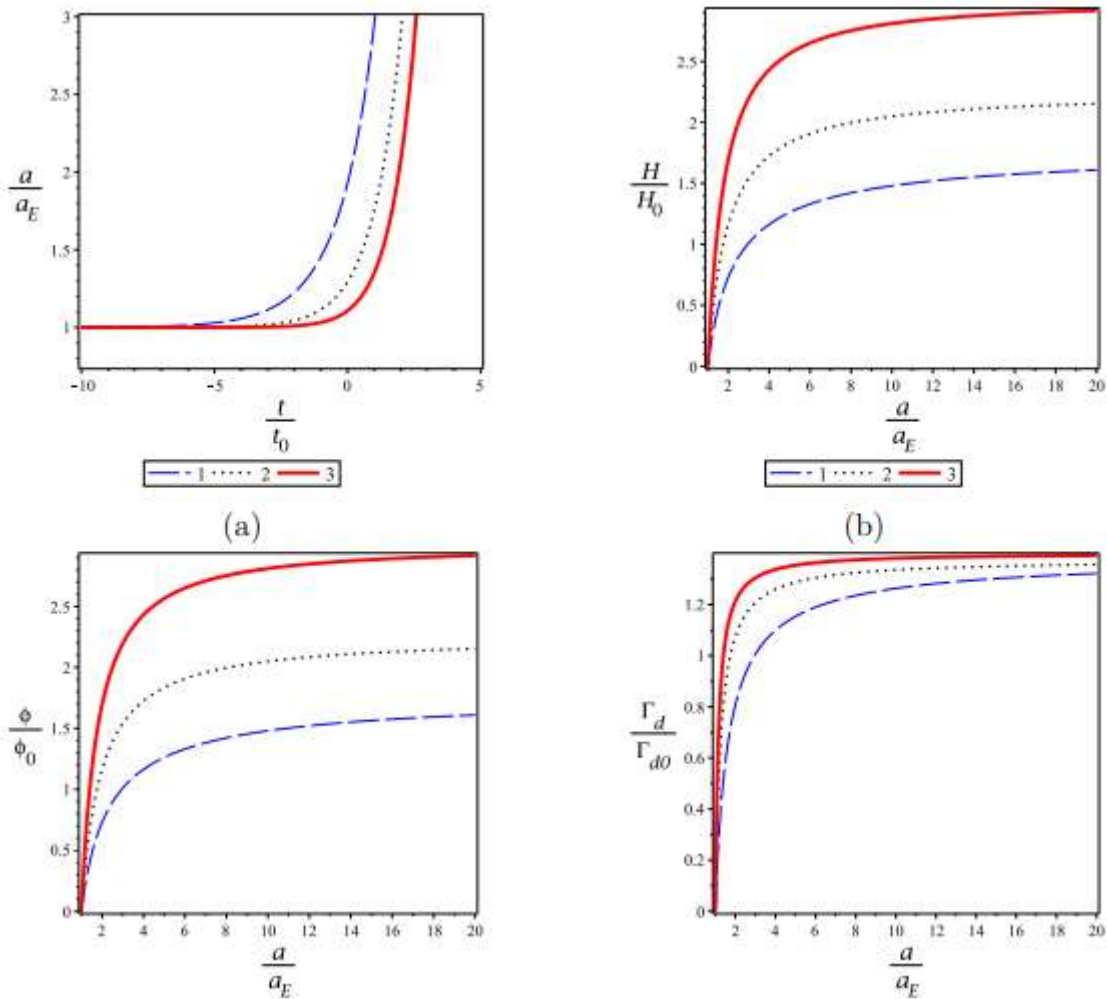


Fig.-3 Complete analysis

Conclusion:

The field at the forefront of comprehending dynamic, real-world systems is non-equilibrium thermodynamics. Its principles offer a unifying framework for analyzing irreversible processes and energy flows, from nanodevices to the global climate. NET will become a pillar of science in the twenty-first century as more research reveals breakthroughs in biology, engineering, and physics. This work explores non-equilibrium thermodynamics, a field that applies classical thermodynamics to systems far from equilibrium. It examines recent advancements in quantum, stochastic, and information thermodynamics, and its applications in environmental science, energy systems, biology, and nanotechnology. The paper presents a model of a diffusive universe with barotropic fluids, discusses dark energy hypotheses, and introduces a cyclic universe. Future work may explore different models of the Universe in diffusive fluid systems.

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