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Tsallis Holographic Dark Energy with Granda-Oliveros Scale in Bianchi-Type V Universe

Murat KORUNUR[1*], Sibel KORUNUR[2]

[1] Munzur University, Engineering Faculty, Electric-Electrical Engineering Department, 62000, Tunceli
[2] Munzur University, Tunceli Vocational School, Electric-Energy Department, 62000, Tunceli

[1]https://orcid.org/0000-0002-8311-9079
[2]https://orcid.org/0000-0003-0687-2400
*Corresponding author: mkorunur@munzur.edu.tr

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ABSTRACT

A wide variety of cosmological observations demonstrate that our universe is in an accelerated expansion phase. Dark energy and dark matter are thought to be two of the causes of this accelerated expansion. Therefore, scientists have been doing many studies on dark energy and matter. In particular, many energy density relations have been reported, and research has been done about space-time structure. In this sense, the Tsallis holographic dark energy model is also in a current and exciting position to understand dark energy. The present study establishes a relationship between the Tsallis Holographic Dark Energy (THDE) model and some scalar fields (quintessence, tachyon, dilaton scalar fields, etc.) specific to the Bianchi-Type V space-time model. The relationship between THDE and Bianchi-Type V space-time model is discussed within the Granda-Oliveros (GO) cut-off framework. The state equation parameter is calculated analytically, and the phase of our universe for this model is graphically investigated. It is found that for all values of the non-additive parameter (except value 2), the EoS parameter behaves as the Λ Cold Dark Model (ΛCDM) in the future. In addition, when looking at the kinetic energy term in all scalar models, the same behavior is observed. Also, the results are analyzed numerically with graphs.

Bianchi Tip-V Evreninde Granda-Oliveros Ölçekli Tsallis Holografik Karanlık Enerji

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ÖZ

Yapılan çok çeşitli kozmolojik gözlemler bize evrenimizin ivmeli genişleme fazında olduğunu göstermektedir. Karanlık enerji ve karanlık madde bu ivmeli genişlemeye sebeplerinden ikisi olduğu düşünülmektedir. Dolayısıyla son zamanlarda bilim insanları karanlık enerji ve karanlık madde üzerine birçok çalışma yapmaktadır. Özellikle çok sayıda enerji yoğunluğu ifadesi yazılarak uzay-zamanın yapısı hakkında araştırmalar yapılmaktadır. Tsallis holografik karanlık enerji (THKE) modeli karanlık enerjiyi anlama noktasında güncel ve heyecan verici bir konumdadır. Çalışmada Bianchi-Tipi V uzay-zaman modeli özelinde Tsallis holografik karanlık enerji modeli ile bazı skaler alanlar (quintessence, takyon, dilaton skaler alanları vb.) arasında bir ilişki kurulmaktadır. THKE ile Bianchi tipi V uzay-zaman modeli arasındaki ilişki, Granda-Oliveros (GO) kesme çerçevesi içinde tartışılmaktadır. Non-additive parametresinin tüm değerleri için (2 değeri hariç), EoS parametresinin gelecekte Λ Soğuk Karanlık Model (ΛSKM) gibi davrandığı bulunmuştur. Bununla birlikte tüm skaler modellerde kinetik enerji terimine bakıldığında aynı davranışın

sergilendiği görülmektedir. Ayrıca sonuçlar grafiklerle sayısal olarak analiz edilmiştir.

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1. Introduction

Recently, the dark matter and dark energy sector, which makes up 95% of our universe, has undoubtedly been the part that has received the most attention from theoretical physicists (Peiris et al., 2003; Abbott et al., 2016; Ade et al., 2018). The other 5% is ordinary matter (Planck Collaboration, 2018). Data from the Planck collaboration, baryon acoustic oscillations, type Ia supernovae, and large-scale galaxy surveys have shown that our universe has accelerated expansion. The most prominent candidate that is thought to cause this expansion is dark energy. One of the primary candidates for dark energy is the generalization of the cosmological constant (Copeland et al., 2006) caused by the negative pressure, where the equation of state (EoS) parameter is equal to -1. Other factors that cause accelerated expansion are general relativity modifications and scalar fields.

Based on the holographic principle, holographic dark energy may cause accelerated expansion. The holographic principle is proposed to clarify the thermodynamics of black holes and is directly related to the entropy of the physical system ('t Hooft, 1993). Additionally, holographic dark energy is compatible with observational data and allows us to understand dark energy. Tsallis and Cirto introduced a new holographic dark energy model called the THDE model using Tsallis generalized entropy (Tsallis and Cirto, 2013). The Bianchi-I (axially symmetric) anisotropic model with a hybrid expansion law by considering k-essence, THDE, and IR (infra-red) cut-off with the Hubble horizon has been studied (Dubey et al., 2019). Another new holographic dark energy in the Bianchi-type universe with k-essence was investigated (Srivastava et al., 2019). Considering the Friedmann–Robertson–Walker model, the quintessence scalar field for the THDE was investigated using various values of the non-additive parameter (Kumar et al., 2022). The non-interacting THDE model and cosmological parameters were studied using the Bianchi-type V space-time model and taken apparent horizon as IR cut-off study (Das and Mahanta, 2022). To review more studies in this area, one can see the following references (Sarkar, 2014; Barboza et al., 2015; Saridakis et al., 2018; Zadeh et al., 2018; Korunur, 2019; Dheepika and Mathew, 2022; Pandey et al., 2022).

Another candidate for dark energy is scalar field, which naturally arises in particle physics, relating the String/M and super-symmetric field theories (Sheykhi and Bagheri, 2011). Due to being a variable EoS parameter, the dark energy candidate has a dynamic character. Therefore, scalar fields are the simplest candidates for the dynamic approach. Many studies have been found out the reconstruction between scalar field and dark energy models (Jorge et al., 2007; Lorenzo et al., 2017; Erkan et al., 2017; Aktas, 2019; Srivastava et al., 2019; Yerzhanov et al., 2019; Korunur, 2021; Mavoa et al., 2022).

The content of our study is as follows: In the next section, an interaction is made with THDE for the Bianchi-Type V space-time model, and the EoS parameter is calculated. Then in the section 3, reconstruction between the THDE and the scalar fields is constructed. The analyzes are evaluated with the help of graphs. The last part is devoted to the conclusion. Some constants. Such as $\hbar, k_B$ and c as one for convenience throughout the study. Mathematica software (Wolfram Research; 2012) is used for graphical analysis and numerical calculations.

2. Interaction THDE and Bianchi -Type V cosmology

Since gravity is a long-range interaction, statistical mechanics is used as an instrument in gravitational systems (Abe, 2001; Mahji, 2017). Tsallis entropy is a generalized and thermodynamical entropy developed using Bekenstein entropy. Considering standard holographic dark energy and Tsallis statistics, a new THDE model is defined (Tsallis and Cirto, 2013). Tsallis generalized entropy is given by:

$$S_T = \gamma A^{\delta}, \tag{1}$$

where γ is an unknown constant while δ is a non-additive parameter and $A = 4\pi L^2$ is the horizon area of the black hole with radius L. The THDE is defined by (Tsallis and Cirto, 2013):

$$\rho_D = \Xi L^{2\delta-4} \tag{2}$$

Here Ξ is a constant with dimension $L^{2-2\delta}$. In this study, we introduce the apparent horizon as a Granda-Oliveros scale (Granda and Oliveros, 2008) as below:

$$L = \left[\mu H^2(t) + \nu \dot{H}(t)\right]^{-2} \ , \tag{3}$$

where dot means the derivative with respect to time, and μ and ν are constants. Using equations (2) and (3), the THDE is obtained as:

$$\rho_D = \Xi\left[\mu H^2(t) + \nu \dot{H}(t)\right]^{2-\delta}. \tag{4}$$

Since the Bianchi-Type V universe model is a generalized and open universe form in the FRW universe model, it is important in dark energy studies (Coles and Ellis, 1994). The following metric gives the spatially homogenous and anisotropic Bianchi-Type V space-time model,

$$ds^2 = -dt^2 + A^2(t)dx^2 + e^{2mx}\left[B^2(t)dy^2 + C^2(t)dz^2\right] \tag{5}$$

where m is a constant. In order to obtain field equations, the Einstein field equation in view of the dark energy can be written as:

$$R^i{}_j - \frac{1}{2} g^i{}_j R = -T_j^{(M)i} - T_j^{(D)i}. \tag{6}$$

Here $T_j^{(M)i}$ and $T_j^{(D)i}$ are energy-momentum tensors of matter and dark energy, which are defined as:

$$T_j^{(M)i} = diag[-\rho^{(M)}, 0,0,0] \tag{7}$$

$$T_j^{(D)i} = diag\left[-1, \omega_x, \omega_y, \omega_z\right]\rho^{(D)}. \tag{8}$$

where $\rho^{(M)}$ and $\rho^{(D)}$ represent energy density of matter and dark energy, respectively, and $p^{(M)}$ is a pressure of matter while $p^{(D)} = \omega\rho^{(D)}$ (ω is represented by the EoS parameter). Using equations (5), (6), and (7)-(8), the following field equations are obtained:

$$\frac{2\dot{A}}{A} - \frac{\dot{B}}{B} - \frac{\dot{C}}{C} = 0, \tag{9}$$

$$\frac{\dot{A}}{A}\frac{\dot{B}}{B} + \frac{\dot{C}}{C}\frac{\dot{B}}{B} + \frac{\dot{A}}{A}\frac{\dot{C}}{C} - \frac{3m^2}{A^2} = \rho^{(M)} + \rho^{(D)}, \tag{10}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}}{A}\frac{\dot{B}}{B} - \frac{m^2}{A^2} = -p^{(D)}, \tag{11}$$

$$\frac{\ddot{C}}{C} + \frac{\ddot{B}}{B} + \frac{\dot{C}}{C}\frac{\dot{B}}{B} - \frac{m^2}{A^2} = -p^{(D)}, \tag{12}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}}{A}\frac{\dot{C}}{C} - \frac{m^2}{A^2} = -p^{(D)}. \tag{13}$$

To obtain the continuity equation, one can combine equations (10)-(13) as:

$$\dot{\rho}^{(M)} + \left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right)\rho^{(M)} + \dot{\rho}^{(D)} + \left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right)\left(\rho^{(D)} + p^{(D)}\right) = 0. \tag{14}$$

Considering energy conservation law $T^{ij}{}_{;j} = 0$ of matter, the equation (14) can be separated as below:

$$\dot{\rho}^{(M)} + 3H\rho^{(M)} = 0, \tag{15}$$

$$\dot{\rho}^{(D)} + 3H(1+\omega)\rho^{(D)} = 0, \tag{16}$$

where the definition of the average Hubble parameter is used:

$$H = \frac{1}{3}\left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right) = \frac{\dot{a}}{a} \tag{17}$$

and a is a time-dependent scale factor ($a = (ABC)^{1/3}$) of the given universe. We consider the special choice of the deceleration parameter (q) (Banerjee and Dos, 2005) as:

$$q = -\frac{a\ddot{a}}{a^2} = -1 + \frac{\beta}{1 + a^{\beta}} \tag{18}$$

where β is a positive constant. When integrating equation (18), it is found that (Bishi and Mahanta, 2015) :

$$a = \left(e^{Q\beta t} - 1\right)^{1/\beta} \tag{19}$$

while Q is an integration constant. From equation (9), it is obtained that $A^2 = BC$. From equations (9), (17), and (19) A can be found, and then taking $B = C^n$ (Collins et al., 1980) B and C can be calculated. Finally, from equations (10)-(13) with equations (15)-(16), the EoS parameter can be obtained in the following form:

$$\omega = \frac{1}{3}\left[\frac{\beta(\delta-2)(\mu-\nu\beta)}{\nu\beta - \mu e^{Q\beta t}} + \beta(2-\delta)\left(e^{-Q\beta t}\right) - 3\right]. \tag{20}$$

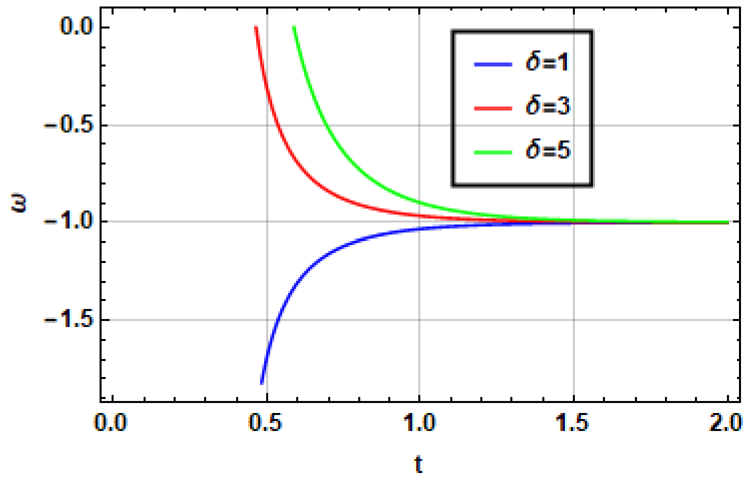

Figure 1. The behavior of EoS parameter with time. The constants are $\beta = 2, Q = 1,\ \mu = 1,\ \nu = 1$

Figure (1) shows the behavior of the EoS parameter in time. According to the graph, the EoS parameter ($\omega < -1$) behaves as phantom dark energy with negative values of $(2\delta - 4)$. On the other hand, when $(2\delta - 4)$ takes positive values, the EoS parameter ($\omega > -1$) tends to quintessence dark energy era. It is concluded that in time the EoS parameter approaches ΛCDM model ($\omega = -1$) (Tavayef et al., 2018; Saridakis et al., 2018; Korunur, 2019).

3. Reconstruction with Scalar Fields

In this subsection, a reconstruction will be made between scalar fields and the TDHE model using the equating method. In other words, an equating is made for the scalar field models considered instead of the energy density defined in the model ($\rho_{SF} \to \rho;\ \rho_{SF}$: energy density of scalar field).

3.1 Reconstruction with Tachyon field

The k-essence model is a model inspired from string theory. In order to make a reconstruction between the THDE and the Tachyon scalar field, the energy and pressure density are described below (Jamil et al., 2011):

$$\rho_T = \frac{V(\phi)}{\sqrt{1-\left(\frac{d\phi}{dt}\right)^2}} \tag{21}$$

$$p_T = -V(\phi)\sqrt{1-\left(\frac{d\phi}{dt}\right)^2} \tag{22}$$

Eliminating $V(\phi)$ from equations (21) and (22) and equating ($\rho_T \to \rho$), $\Upsilon_T \equiv \left(\frac{d\phi}{dt}\right)^2$ can be obtained:

$$\Upsilon_T = \frac{1}{3}\beta(\delta - 2)\left(\frac{\mu - \nu\beta}{\nu\beta - \mu e^{Q\beta t}} - e^{-Q\beta t}\right), \tag{23}$$

which means the kinetic energy term of a scalar field. Then eliminating $\left(\frac{d\phi}{dt}\right)^2$ from equations (21) and (22), we obtain the scalar potential of the scalar field as follows:

$$V_T = \Xi\left[\frac{Q^2 e^{Q\beta t}\left(\mu e^{Q\beta t} - \nu\beta\right)}{(e^{Q\beta t} - 1)^2}\right]^{2-\delta}\left[1 - \frac{1}{3}\beta(\delta - 2)\left(\frac{\mu - \nu\beta}{\nu\beta - \mu e^{Q\beta t}} - e^{-Q\beta t}\right)\right]^{\frac{1}{2}}. \tag{24}$$

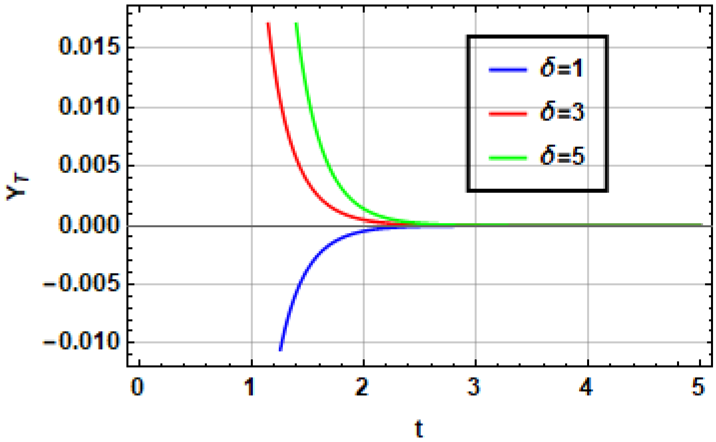

Figure 2. The behavior of tachyonic kinetic energy term with time. Here, the constants are $\beta = 2, Q = 1,\ \mu = 1,\ \nu = 1$

According to Figure 2, the kinetic energy term decreases in time and goes to zero for positive values of $(2\delta - 4)$; on the contrary, for negative values of $(2\delta - 4)$, the kinetic energy term increases to zero in time.

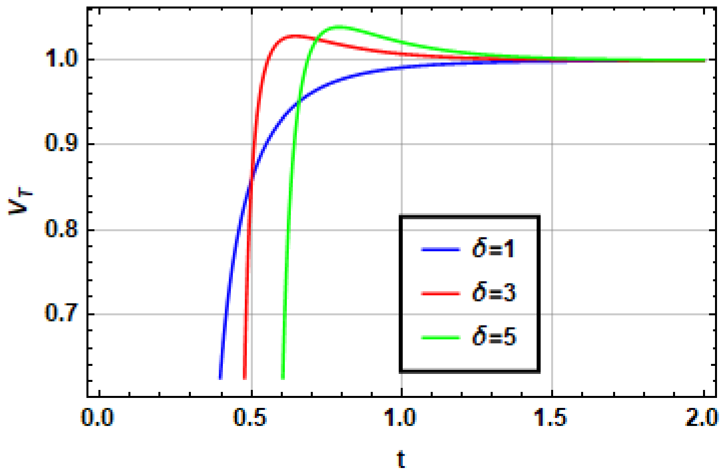

Figure 3. The behavior of scalar potential term with time. Here, the constants are $\beta = 2, Q = 1,\ \mu = 1,$ $\nu = 1, \Xi = 1$

With all the values of the δ in Figure 3, the scalar potential increases rapidly and approaches a constant value over time.

3.2 Reconstruction with Quintessence field

The energy and pressure density of the quintessence field was given by Jamil et al.(2011):

$$\rho_q = \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 + V(\phi) \tag{25}$$

$$p_q = \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 - V(\phi). \tag{26}$$

Using equations (25) and (26), it can be found that correspondence between the THDE and the kinetic energy term and scalar potential of the quintessence scalar field can be found as, respectively,

$$\Upsilon_q = \frac{Q^2\beta(\delta-2)\Xi\left[(\nu\beta-2\mu)e^{Q\beta t}+\nu\beta\right]}{3(e^{Q\beta t}-1)^2}\left[\frac{Q^2e^{Q\beta t}\left(\mu e^{Q\beta t}-\nu\beta\right)}{(e^{Q\beta t}-1)^2}\right]^{1-\delta} \tag{27}$$

$$V_q = \frac{\Xi}{6}\left[\frac{Q^2e^{Q\beta t}\left(\mu e^{Q\beta t}-\nu\beta\right)}{(e^{Q\beta t}-1)^2}\right]^{2-\delta}\left[\frac{\beta(\delta-2)(\mu-\nu\beta)}{\mu e^{Q\beta t}-\nu\beta}+\beta(\delta-2)e^{-Q\beta t}+6\right]. \tag{28}$$

Like the tachyon field, the kinetic energy in the quintessence field also approaches zero over time in Figure 4. In Figure 5, again, the scalar potential of the quintessence field the scalar potential increases rapidly and approaches the constant value.

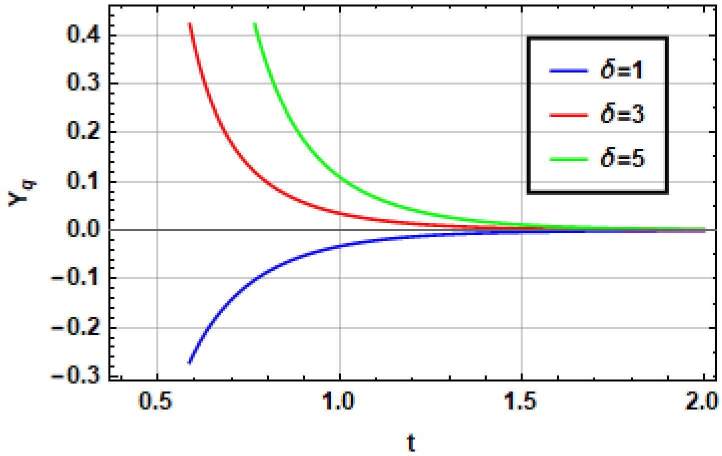

Figure 4. The behavior of quintessence scalar field kinetic energy term with time. Here, constants are $\beta = 2, Q = 1,\ \mu = 1,\ \nu = 1$

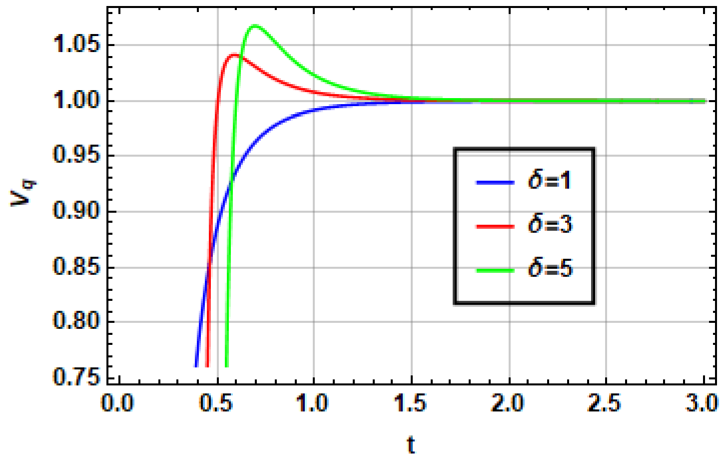

Figure 5. The behavior of quintessence scalar potential term with time. Here, the constants are $\beta = 2, Q = 1,\ \mu = 1,\ \nu = 1, \Xi = 1$

3.3 Reconstruction with k-essence field

It is a model in which the kinetic energy term of the scalar field is dominant, and the energy and pressure density were written by Copeland et al. (2006):

$$\rho_k = V(\phi)(3\chi^2 - \chi) \tag{29}$$

$$p_k = V(\phi)(\chi^2 - \chi) \tag{30}$$

where χ represents a non-canonical kinetic energy: $\chi \equiv \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2$. Again eliminating scalar potential from equations (29)-(30) and equating ($\rho_k \to \rho,\ \omega_k \to \omega$) the non-canonical kinetic energy is found as:

$$\chi = \frac{\omega_k - 1}{3\omega_k - 1} \tag{31}$$

and scalar potential is:

$$V = \frac{1}{2}\rho_k(1 - \omega_k)\left(\frac{3 + \omega_k}{\omega_k + 1}\right). \tag{32}$$

Using equations (4) and (20) in equations (31) and (32), it is found that the non-caconical kinetic energy and the scalar field in explicit form, respectively:

$$\chi = \frac{2\mu e^{Q\beta t}\left[3e^{Q\beta t} + \beta(\delta - 2)\right] - \nu\beta\{[\beta(\delta - 2) + 6]e^{Q\beta t} + \beta(\delta - 2)\}}{6\mu e^{Q\beta t}[2e^{Q\beta t} + \beta(\delta - 2)] - 2\nu\beta\{[\beta(\delta - 2) + 4]e^{Q\beta t} + \beta(\delta - 2)\}} \tag{33}$$

$$V_k = \frac{Q^2\left[\frac{2\mu Q^2 e^{Q\beta t}\left(\mu e^{Q\beta t} - \nu\beta\right)}{(e^{Q\beta t} - 1)^2}\right]^{1-\delta}}{6\beta^2(\delta - 2)^2(e^{Q\beta t} - 1)^2[(\nu\beta - 2\mu)e^{Q\beta t} + \nu\beta]^2} \times \frac{\left(3e^{Q\beta t} + \beta(\delta - 2)\right) - \nu\beta\{[\beta(\delta - 2) + 6]e^{Q\beta t} + \beta(\delta - 2)\}}{6\beta^2(\delta - 2)^2(e^{Q\beta t} - 1)^2[(\nu\beta - 2\mu)e^{Q\beta t} + \nu\beta]^2} \tag{34}$$

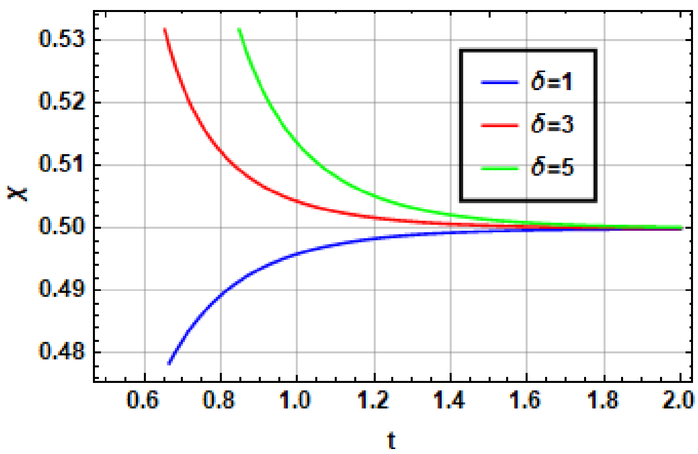

Figure 6. The behavior scalar field of k-essence kinetic energy term with time. Here, the constants are $\beta = 2, Q = 1,\ \mu = 1,\ \nu = 1$

Finally, this model examines the time variation of components of the scalar field. Again, kinetic energy is constant over time (Figure 6), as in previous scalar field models. However, unlike other scalar fields, the scalar potential increases continuously over time for the k-essence scalar field. As the delta value increases, this increased rate becomes slower.

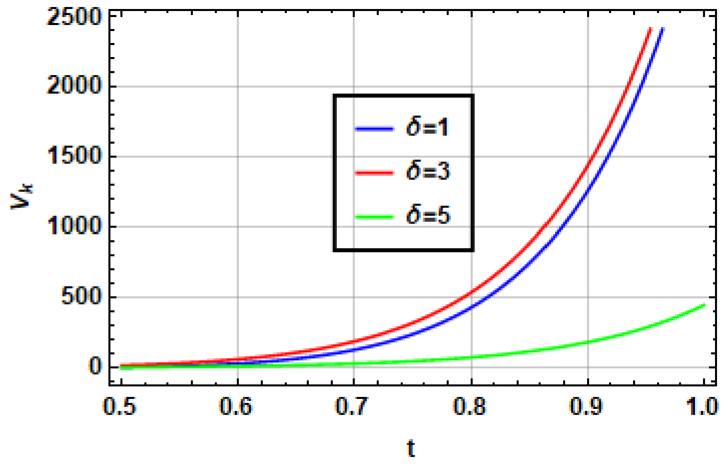

Figure 7. The behavior of scalar potential of k-essence term with time. Here, the constants are $\beta = 2, Q = 1$, $\mu = 1,\ \nu = 1, \Xi = 1$

4. Conclusions

Studies to understand dark energy continue in the literature. As new dark energy models are defined, it will be get closer to solving this mystery in the universe. In this contex using a new dark energy model called the THDE, reconstruction between the THDE and scalar fields such as Quintessence, k-essence, and Tachyon is proposed. Also, in the THDE model, the time dependence of the EoS parameter is studied within the Granda-Oliveros (GO) cut-off framework. The negative values of $(2\delta - 4)$, the EoS parameter acts as phantom dark energy. Besides, with positive values of $(2\delta - 4)$, the EoS parameter behaves as quintessence dark energy. For all values of δ (except $\delta = 2$), the EoS parameter acts as the ΛCDM model in the future. The same behavior is seen when we look at the kinetic energy term in all scalar models. However, the scalar potential exhibits similar behavior in other tachyon and quintessence fields other than the k-essence scalar field.

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Statement of Conflict of Interest

Authors have declared no conflict of interest.

Author's Contributions

The contribution of the authors is equal.

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