Hindawi
Advances in High Energy Physics
Volume 2018, Article ID 9534279, 11 pages
https://doi.org/10.1155/2018/9534279

Research Article

Study of Homogeneous and Isotropic Universe in $f(R, T^{\varphi})$ Gravity

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Received 7 February 2018; Revised 25 May 2018; Accepted 26 June 2018; Published 26 July 2018

Academic Editor: Ricardo G. Felipe

This paper is devoted to study the cosmological behavior of homogeneous and isotropic universe model in the context of $f(R, T^{\varphi})$ gravity, where φ is the scalar field. For this purpose, we follow the first-order formalism defined by $H = W(\varphi)$. We evaluate Hubble parameter, effective equation of state parameter (ω^{eff}), deceleration parameter, and potential of scalar field for three different values of $W(\varphi)$. We obtain phantom era in some cases for the early times. It is found that exponential expression of $W(\varphi)$ yields ω^{eff} independent of time for flat universe and independent of model parameter otherwise. It is concluded that our model corresponds to ΛCDM for both initial and late times.

1. Introduction

The most striking and fascinating area in cosmology is the current accelerated expansion of the universe suggested by various observations. The agent causing this expansion is termed as dark energy and it violates the strong energy condition. Cosmological observations reveal that our universe is approximately homogeneous and isotropic at large scales [1] described by the standard FRW model. Inclusion of cosmological constant (Λ) to the standard model leads to Λ cold dark matter (ΛCDM) model. In general relativity (GR), the ΛCDM model explains the expanding behavior of the universe where Λ is supposed to play the role of dark energy.

Despite its many features, there are two major issues associated with this model named as fine tuning and coincidence problems [2]. The huge difference between the vacuum energy density and the ground state energy suggested by quantum field theory leads to the first issue. For this model, the densities of dark matter and dark energy are of the same order leading to cosmological coincidence problem. In order to resolve such and other open issues, alternative models of dark energy were proposed by modifying either matter or geometric part of the Einstein-Hilbert action. Modified matter models [3–7] are quintessence, phantom, K-essence, holographic dark energy, and Chaplygin gas. Some examples of modification in geometric part are scalar-tensor theory, $f(R)$ and $f(R, T)$ theories of gravity.

Harko *et al.* [8] proposed $f(R, T)$ gravity as a generalized modified theory where R is the Ricci scalar and T is the trace of energy-momentum tensor. The dependence on T is included due to the considerations of exotic fluids or quantum effects. The coupling of curvature and matter yields interesting consequences such as covariant derivative of the energy-momentum tensor which is no longer zero implying the existence of an extra force as well as nongeodesic path of particles. In cosmological scenario, it can explain the problem of galactic flat rotation curves as well as dark matter and dark energy interactions [9]. Jamil *et al.* [10] introduced some cosmic models in this gravity and showed that dust fluid can reproduce ΛCDM model. Sharif and Zubair [11] explored thermodynamics and concluded that generalized second law of thermodynamics is valid for phantom as well as nonphantom phases. The same authors [12] established energy conditions and constraints for the stability of power-law models.

Singh and Singh [13] discussed the reconstruction of $f(R, T)$ gravity models in the presence of perfect fluid and showed that $f(R, T)$ extra terms can represent phantom dark

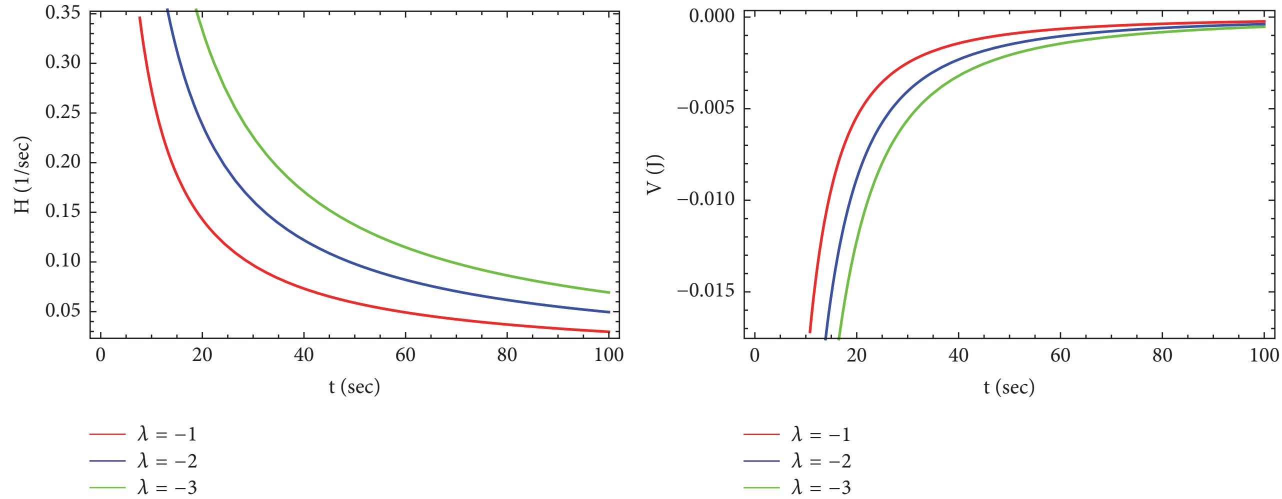

Figure 1: Plots of H and V versus t for $W(\varphi) = e^{b_1\varphi}$, $b_1 = 1(1/sec)$, and $c_1 = 1$ when $k = 0$.

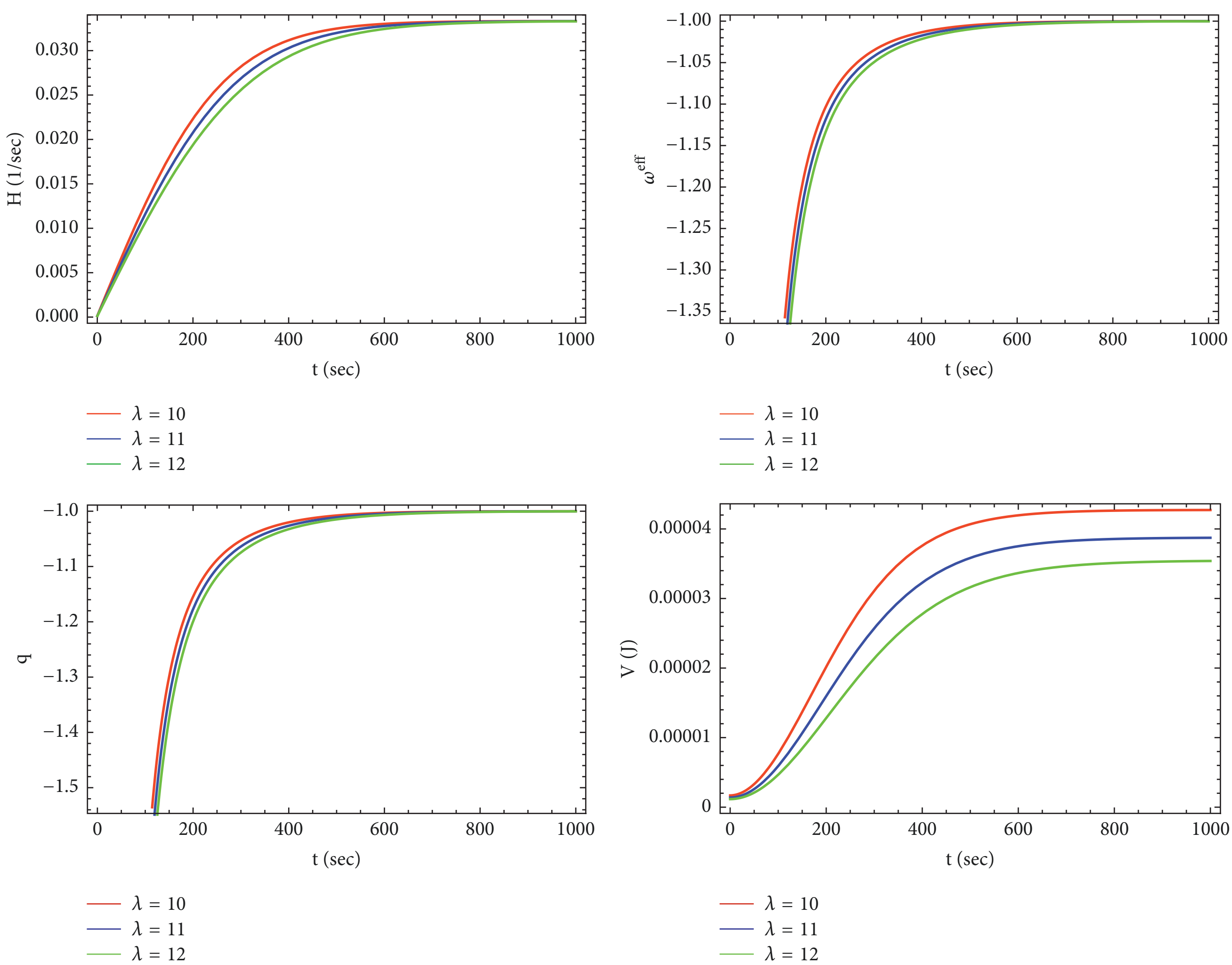

Figure 2: Plots of H, ω^{eff}, q, and V versus t for $W(\varphi) = b_2(\varphi^2/3 - \varphi)$, $b_2 = 0.05(1/sec)$, and $c_2 = 1$ when $k = 0$.

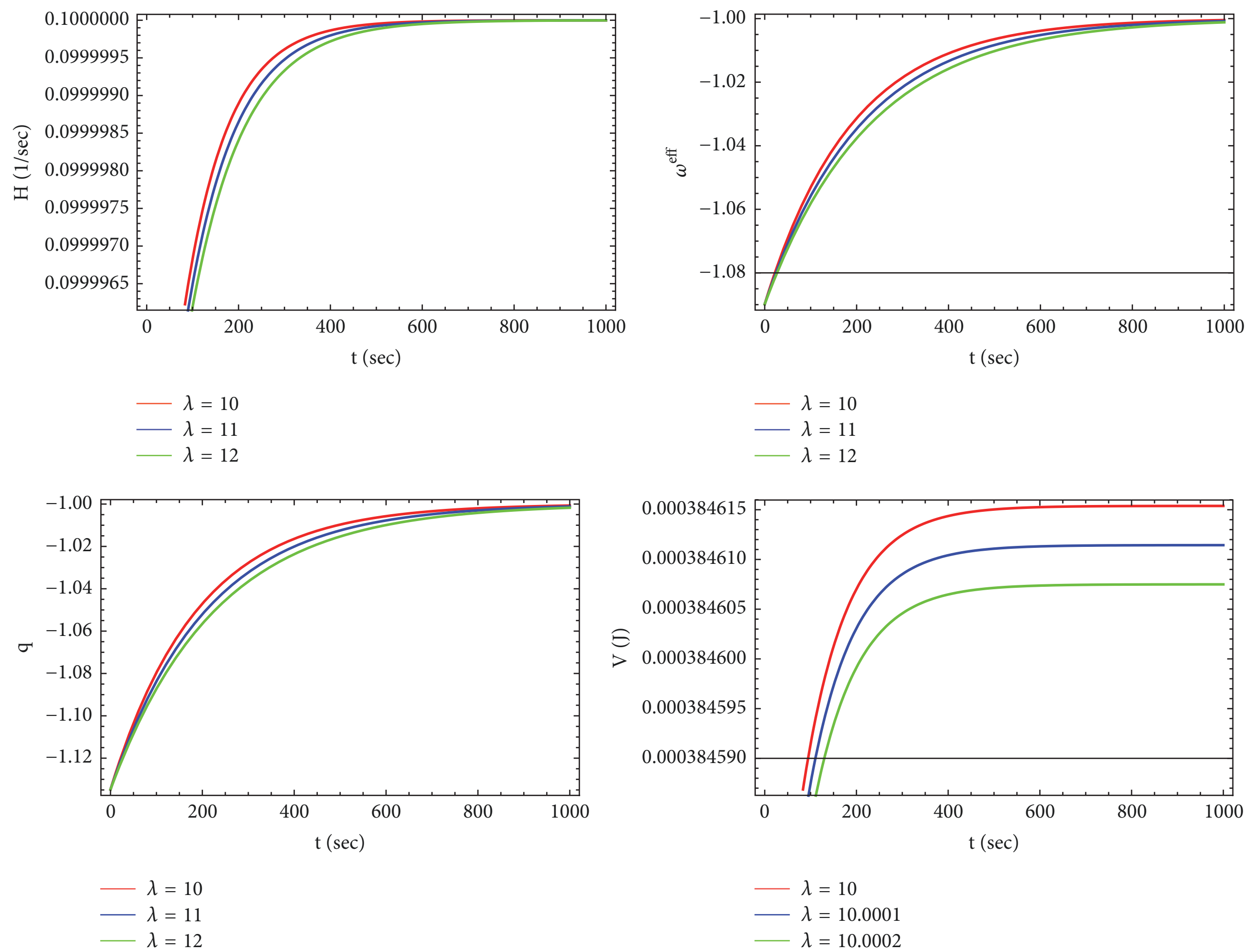

Figure 3: Plots of H, ω^{eff}, q, and V versus t for $W(\varphi) = b_3 \sin \varphi$, $b_3 = 0.1(1/sec)$, and $c_3 = 5$ when $k = 0$.

energy as well as cosmological constant in the presence and absence of perfect fluid, respectively. Singh and Kumar [14] explored the role of bulk viscosity using FRW model with perfect fluid and found that bulk viscosity provides a supplement for expansion. In literature [15–17], the higher dimensions are also explored in the framework of $f(R, T)$ gravity. Moraes *et al.* [18] studied hydrostatic equilibrium condition for neutron stars with a specific form of equation of state (EoS) and found that the extreme mass can cross observational limits.

In [8], Harko *et al.* also discussed $f(R, T^{\varphi})$ theory where T^{φ} is the trace of energy-momentum tensor of a scalar field. Scalar fields have extensively been studied in cosmology during the last three decades. Yukawa is the pioneer to introduce scalar field in physics which naturally has an EoS $p = -\rho$ and hence is expected to play a vital role in modern cosmology as well as astrophysics [19]. Alves *et al.* [20] confirmed the existence of gravitational waves for extra polarization modes in both $f(R, T)$ as well as $f(R, T^{\varphi})$ theories.

Halliwell [21] explored the role of scalar field with exponential potential and also discussed some examples that yield exponential potential. Virbhadra *et al.* [22] studied the effect of scalar field in gravitational lensing and explored the features of lens specified by mass and charge of scalar field. Nunes and Mimoso [23] worked on phase-plane analysis for a flat FRW model in the presence of perfect fluid as well as self-interacting scalar field. They showed that the scalar field potential having positive, monotonic, and asymptotically exponential behavior leads to global attractor. Das and Banerjee [24] explored that the scalar field can produce deceleration and acceleration phases of cosmos by considering an energy transfer between scalar field and dark matter.

Bazeia *et al.* [25] introduced the first-order formalism for scalar field models and also discussed some examples of cosmological interest. In [26], the authors extended this formalism for scalar fields with tachyonic dynamics. Recently, Moraes and Santos [27] presented a cosmological picture in $f(R, T^{\varphi})$ gravity in the absence of matter by considering flat FRW model. They started with the relation $\dot{\varphi} = -dW/d\varphi$ which comes from the field equations of GR via the above-mentioned formalism. We have applied this formalism to Bianchi type-I universe model (with no matter present) and concluded that the exponential form of $W(\varphi)$ can explain all the stages of the universe evolution [28].

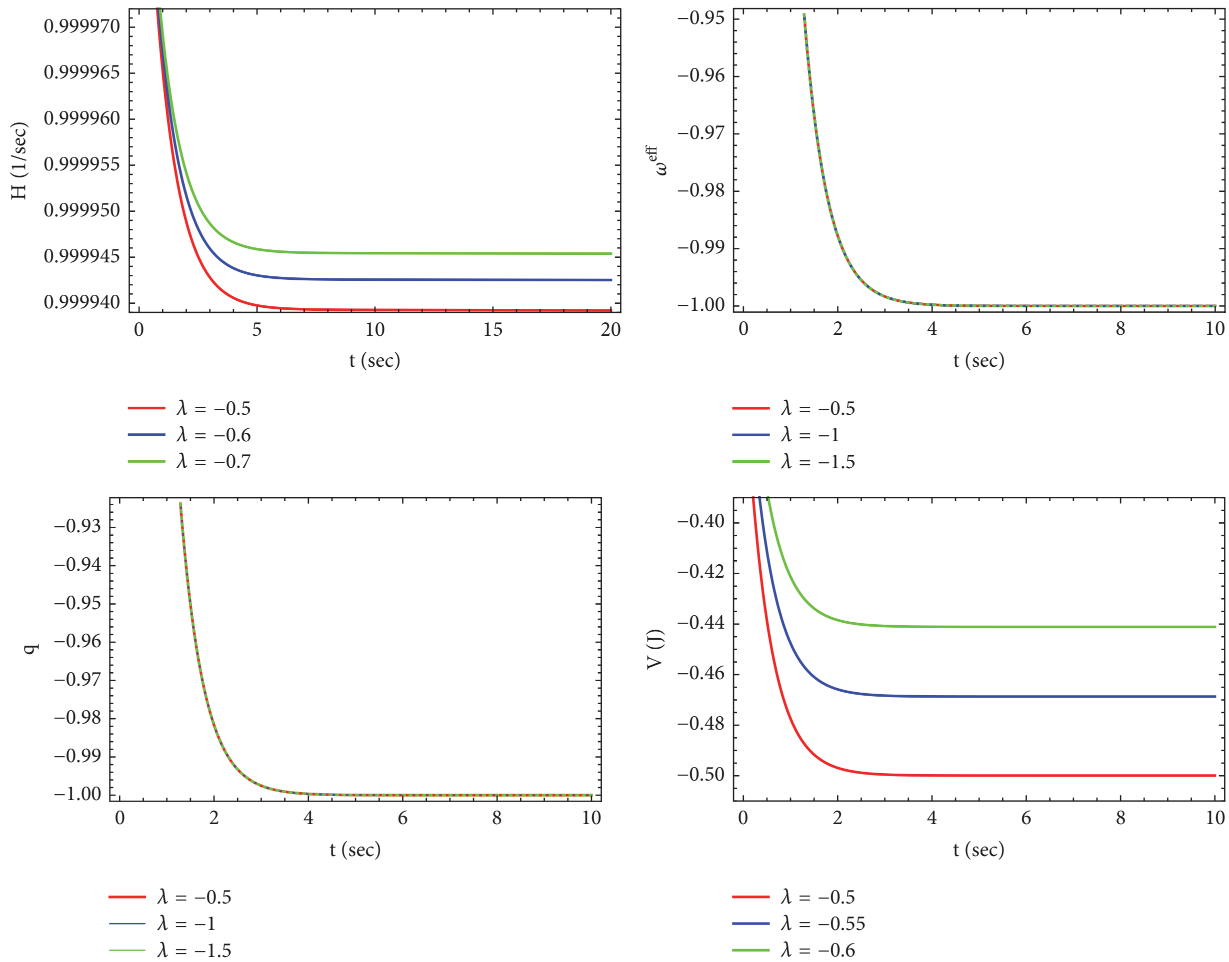

Figure 4: Plots of H, ω^{eff}, q, and V versus t for $W(\varphi^-) = e^{b_1\varphi^-}$, $b_1 = 0.0001(1/sec)$, and $\varphi^-(0) = 0.1$ when $k = 1$.

The motivation for neglecting matter action is that $f(R,T)$ framework cannot describe the radiation-dominated era because in that phase the value of T for perfect fluid is zero and $f(R,T)$ theory is reduced to $f(R)$ scenario [27]. Moreover, Alves *et al.* [20] showed that for gravitational wave passing through vacuum with no extra polarization modes are induced due to curvature matter coupling as $T = 0$ in vacuum. On the other hand, the same phenomenon in $f(R,T^{\varphi})$ is controlled by the assumed model. Hence, the study of radiation phase as well as any phenomenon in vacuum has become a crucial issue to be addressed. In this regard, Moraes introduced an extra dimension [29] and in [30] he considered a varying speed of light to obtain the solutions in radiation phase.

In this paper, we explore cosmology of generalized FRW universe model using the same action used in [27] and with the fundamental assumption of first order formalism, i.e., $H = W(\varphi)$ in $f(R,T^{\varphi})$ gravity. The plan of the paper is as follows. In the next section, we formulate the field equations and find the values of H, ω^{eff}, q, and $V(\varphi)$. We also discuss graphical behavior of these parameters for different models of $W(\varphi)$. The last section provides the obtained results.

2. Field Equations and First-Order Formalism

The action for $f(R,T^{\varphi})$ gravity is given by

$$S = \int d^4x\sqrt{-g}\left[f\left(R,T^{\varphi}\right) + \mathscr{L}\left(\varphi,\partial_{\nu}\varphi\right)\right], \tag{1}$$

where we assume that $16\pi G = c = 1$. In the following, we use the model $f(R,T^{\varphi}) = -R/4 + \lambda T^{\varphi}$ [27], where λ is a constant known as model parameter. The corresponding field equations are

$$G_{\alpha\beta} = 2\left(T^{\varphi}_{\alpha\beta} - g_{\alpha\beta}\lambda T^{\varphi} - 2\lambda\partial_{\alpha}\varphi\partial_{\beta}\varphi\right), \tag{2}$$

where $G_{\alpha\beta}$ is the Einstein tensor and $T^{\varphi}_{\alpha\beta}$ represents the energy-momentum tensor of a scalar field. For a real φ, the Lagrangian density and the energy-momentum tensor are given by

$$\mathscr{L} = \frac{1}{2}\partial_{\alpha}\varphi\partial^{\alpha}\varphi - V\left(\varphi\right), \tag{3}$$

$$T^{\varphi}_{\alpha\beta} = \partial_{\alpha}\varphi\partial_{\beta}\varphi - g_{\alpha\beta}\mathscr{L}, \tag{4}$$

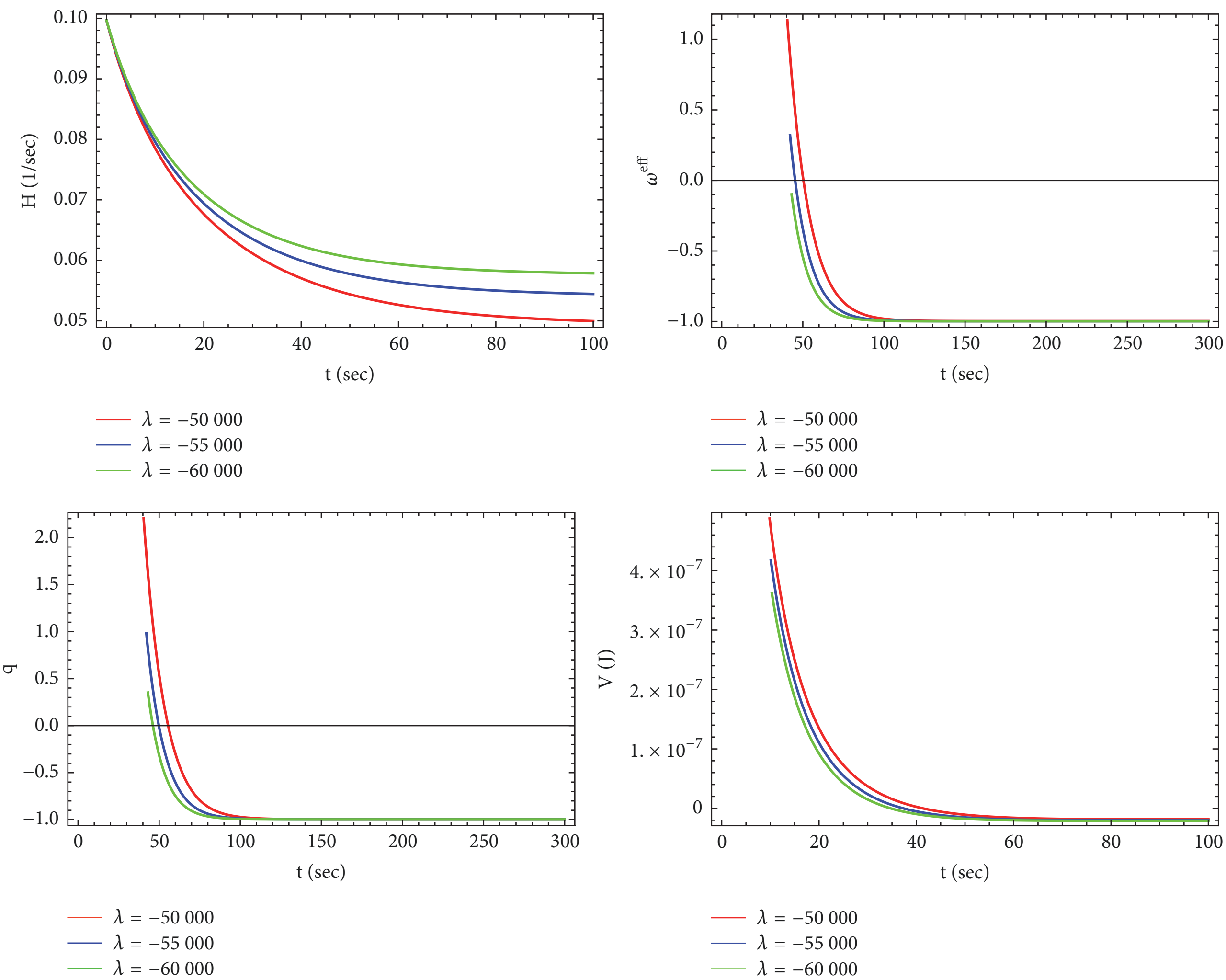

FIGURE 5: Plots of H, ω^{eff}, q, and V versus t for $W(\varphi^{-}) = b_2((\varphi^{-})^2/3 - \varphi^{-})$, $b_2 = -1(1/sec)$, and $\varphi^{-}(0) = 0.1$ when $k = 1$.

where $V(\varphi)$ denotes the self-interacting potential. The trace of the energy-momentum tensor is

$$T^{\varphi} = \dot{\varphi}^2 + 4V(\varphi), \tag{5}$$

dot denotes derivative with respect to t.

The line element of FRW model is given by

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right), \tag{6}$$

where $a(t)$ is the scale factor and k represents curvature of the space. For $k = 0, 1, -1$, we have flat, closed, and open universe model, respectively. The corresponding field equations are

$$\frac{3}{2}H^2 = \left(\frac{1}{2} - \lambda\right)\dot{\varphi}^2 + (4\lambda - 1)V - \frac{3}{2}\frac{k}{a^2}, \tag{7}$$

$$\frac{3}{2}H^2 + \dot{H} = -\left(\frac{1}{2} - \lambda\right)\dot{\varphi}^2 + (4\lambda - 1)V - \frac{1}{2}\frac{k}{a^2}, \tag{8}$$

which yield the expression of $\dot{H}$ as

$$\dot{H} = -(1 - 2\lambda)\dot{\varphi}^2 + \frac{k}{a^2}. \tag{9}$$

The equation of motion for scalar field is obtained as

$$(1 - 2\lambda)(\ddot{\varphi} + 3H\dot{\varphi}) + (1 - 4\lambda)V_{\varphi} = 0, \tag{10}$$

where subscript φ indicates derivative with respect to φ. Following the first-order formalism [25], the Hubble parameter is given by

$$H = W(\varphi). \tag{11}$$

The expressions of $V(\varphi)$ and ω^{eff} from the field equations become

$$V(\varphi) = \frac{1}{4\lambda - 1}\left[\frac{3}{2}W^2 - \left(\frac{1}{2} - \lambda\right)\dot{\varphi}^2 + \frac{3}{2}\frac{k}{a^2}\right], \tag{12}$$

$$\omega^{eff} = \frac{p^{eff}}{\rho^{eff}} = -\left[1 + \frac{\dot{\varphi}^2(4\lambda - 2)}{3(W^2 + k/a^2)}\right], \tag{13}$$

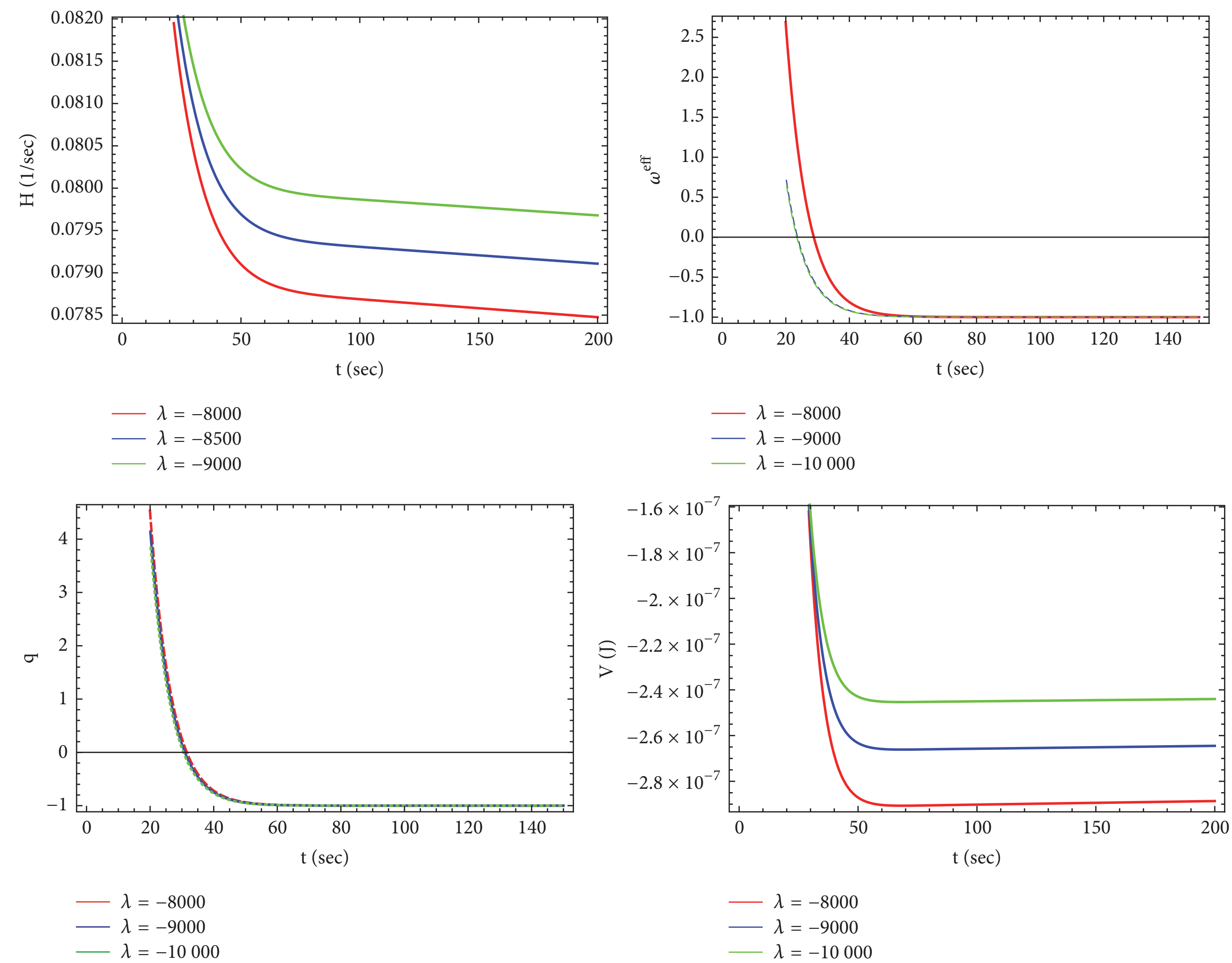

Figure 6: Plots of H, ω^{eff}, q, and V versus t for $W(\varphi^{-}) = b_3 \sin \varphi^{-}$, $b_3 = 0.2(1/sec)$, and $\varphi^{-}(0) = 0.5$ when $k = 1$.

where ρ^{eff} and p^{eff} are

$$\rho^{eff} = \left(\frac{1}{2} - \lambda\right)\dot{\varphi}^2 + (1 - 4\lambda)V,$$
$$p^{eff} = \left(\frac{1}{2} - \lambda\right)\dot{\varphi}^2 - (1 - 4\lambda)V, \tag{14}$$

while the decelerating parameter is defined as

$$q = \frac{1}{2}\left(1 + 3\omega^{eff}\right)\left(1 + \frac{1}{a^2H^2}\right). \tag{15}$$

Substituting H from (11) into (9), we have

$$(1 - 2\lambda)\dot{\varphi}^2 + W_{\varphi}\dot{\varphi} - \frac{k}{a^2} = 0, \tag{16}$$

which is a quadratic equation in $\dot{\varphi}$. It has two roots

$$\dot{\varphi} = \frac{-W_{\varphi} \pm \sqrt{W_{\varphi}^2 + (4k/a^2)(1 - 2\lambda)}}{2(1 - 2\lambda)}, \tag{17}$$

each of which is a first-order differential equation. We find the solution for the following three expressions of $W(\varphi)$.

(1) $W(\varphi) = e^{b_1\varphi}$, where b_1 is a real constant. The scalar field potentials followed by this value of $W(\varphi)$ are of much interest. When $b_1 = 1$, it reproduces some negative potential and $b_1 = 2$ leads to potential which presents spontaneous symmetry breaking [25].

(2) $W(\varphi) = b_2(\varphi^2/3 - \varphi)$, where b_2 is a real constant. It represents a φ^4 type of model [31].

(3) $W(\varphi) = b_3 \sin\varphi$, b_3 is a real constant. It is a sine-Gordon type of model [32].

2.1. Flat Universe ($k = 0$). In this case, (17) implies that either

$$\dot{\varphi} = 0$$
$$\text{or } \dot{\varphi} = -\frac{W_{\varphi}}{1 - 2\lambda}. \tag{18}$$

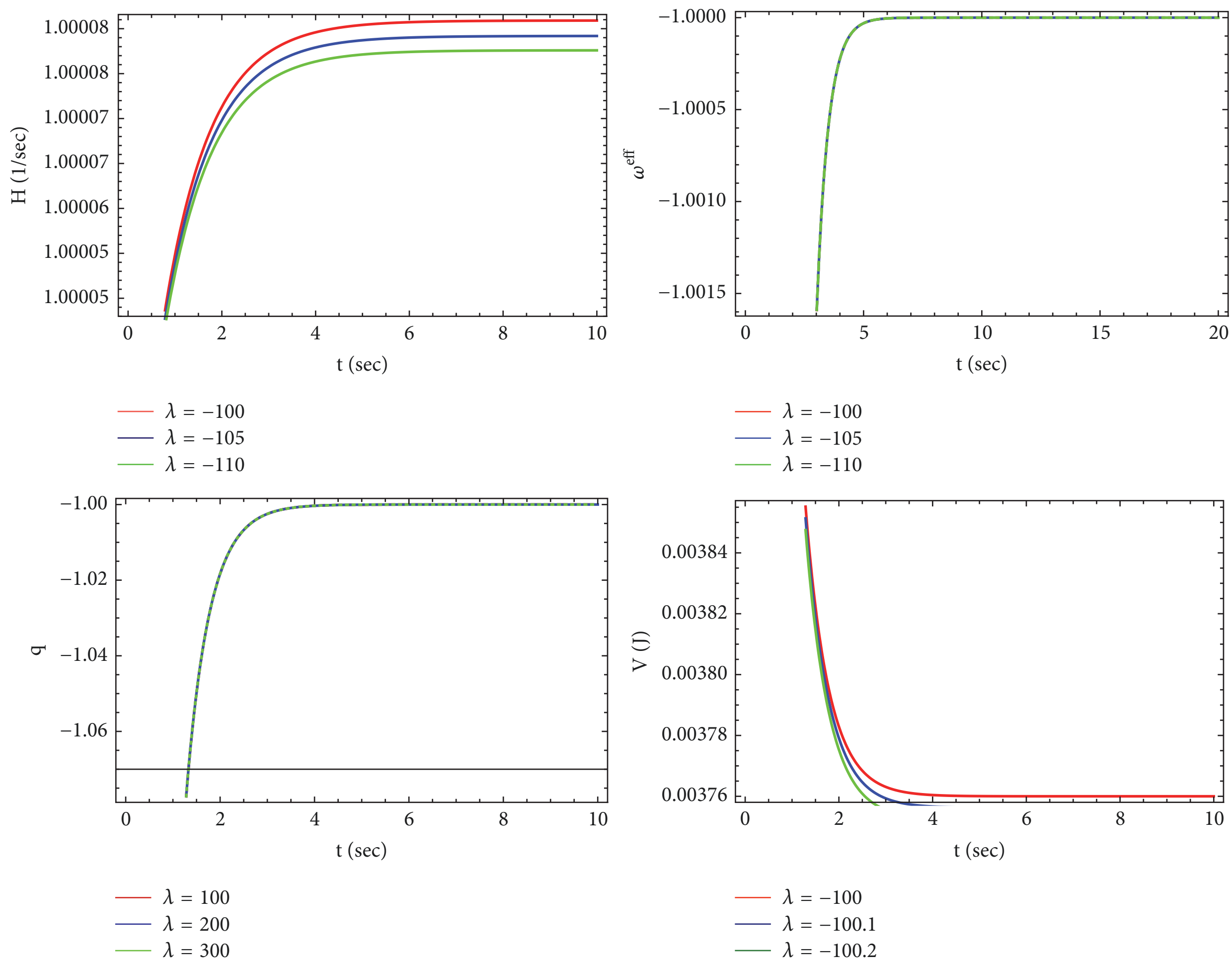

FIGURE 7: Plots of H, ω^{eff}, q, and V versus t for $W(\varphi^{-}) = e^{b_1\varphi^{-}}$, $b_1 = 0.001(1/sec)$, and $\varphi^{-}(0) = 0.01$ when $k = -1$.

TABLE 1: Solution of $\dot{\varphi} = -W_{\varphi}/(1-2\lambda)$.

$W(\varphi)$	$\varphi(t)$
$e^{b_1\varphi}$	$\frac{1}{b_1}\ln\left[\frac{1-2\lambda}{b_1^2(t+c_1)}\right]$
$b_2(\frac{\varphi^3}{3}-\varphi)$	$\tanh\left[\frac{b_2(t+c_2)}{1-2\lambda}\right]$
$b_3\sin\varphi$	$2\arctan\left[\tanh\left[\frac{b_3 t}{4\lambda-2}+\frac{c_3}{2}\right]\right]$

For $\dot{\varphi} = 0$, we have constant value of φ and consequently (11)-(15) yield

$$\begin{aligned} H &= \text{constant}, \\ \omega^{eff} &= -1, \\ q &= -1, \\ V(\varphi) &= \text{constant}, \end{aligned} \tag{19}$$

which represents ΛCDM model. The solutions of the second option in (18) for all forms of $W(\varphi)$ are given in Table 1, where c_1, c_2, and c_3 are constants of integration. The graphical behavior of the corresponding H, ω^{eff}, q, and $V(\varphi)$ is shown in Figures 1–3. For graphical analysis, we have taken the free parameters such that when $\omega^{eff} < -1$, H is increasing while if $\omega^{eff} > -1$, then H is decreasing and when $\omega^{eff} = -1$, H is constant [33]. According to standard cosmology [34], $H \propto t^{-1}$ after inflation and it becomes constant with the passage of time. We see that the Hubble parameter shows this behavior only for exponential value of $W(\varphi)$. The Hubble parameter and λ are inversely related, i.e., decrease in λ increases H and vice versa for all values of $W(\varphi)$.

The exponential value of $W(\varphi)$ yields the following time independent expressions for ω^{eff} and q

$$\omega^{eff} = -1 + \frac{2b_1^2}{3(1-2\lambda)}, \tag{20}$$

$$q = -1 + \frac{b_1^2}{(1-2\lambda)}, \tag{21}$$

Equation (20) shows that ω^{eff} can have different values depending upon the arbitrary constants b_1 and λ. For polynomial and trigonometric forms of $W(\varphi)$, it initially falls

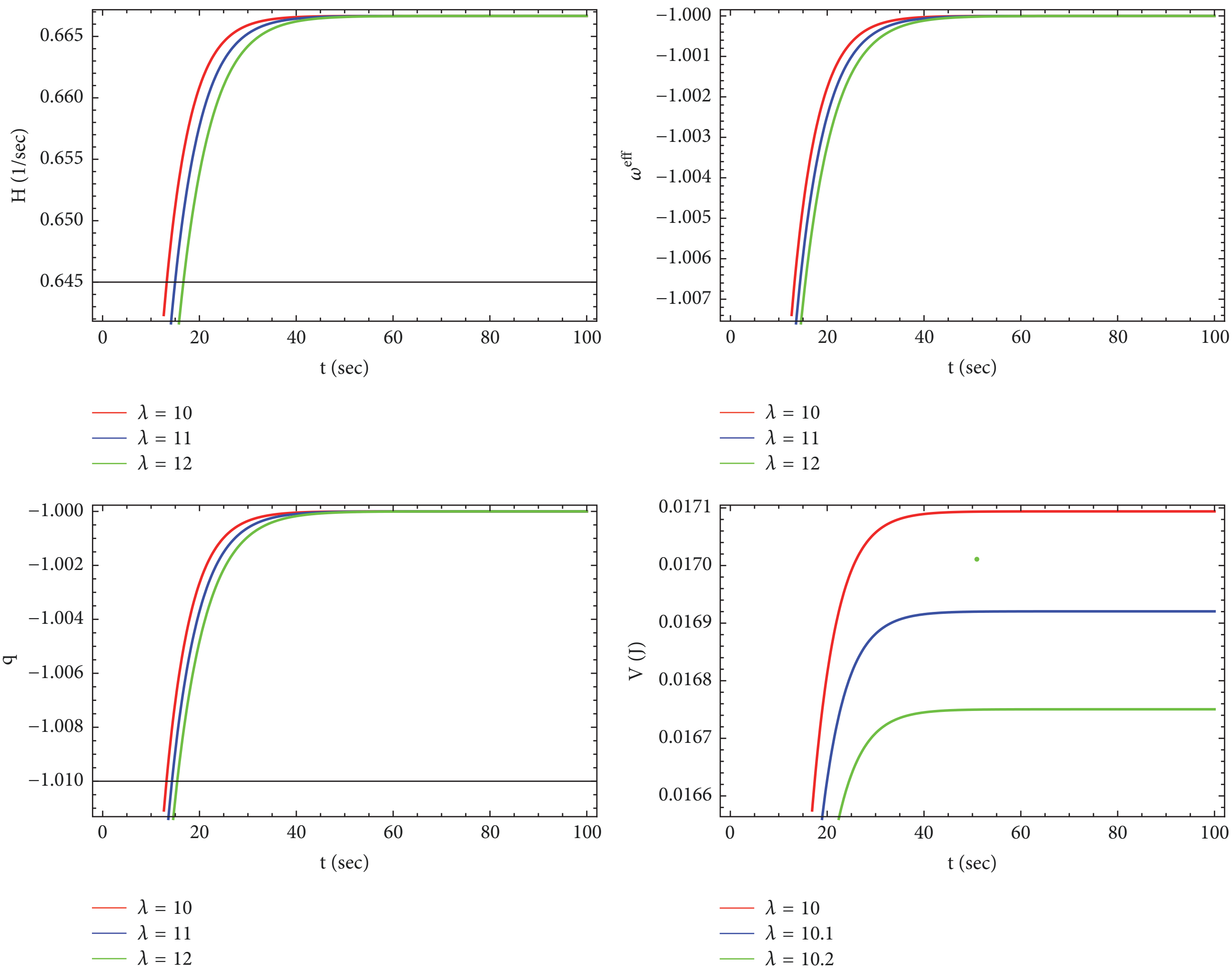

FIGURE 8: Plots of H, ω^{eff}, q, and V versus t for $W(\varphi^-) = b_2((\varphi^-)^2/3 - \varphi^-)$, $b_2 = -1(1/sec)$, and $\varphi^-(0) = 0.1$ when $k = -1$.

in phantom regime and then approaches to ΛCDM model as time increases. The increase in λ decreases ω^{eff} for the second and third forms of $W(\varphi)$. We see that ω^{eff} is -1 for all values of λ at late times. The value of deceleration parameter, given in (21) indicates that we have accelerated expansion phase when $b_1^2 < 1 - 2\lambda$ and vice versa. The graphs of q in Figures 2 and 3 show that the rate of expansion is decreasing with time. The potential of scalar field is negative as well as increasing for the first form while positive and increasing for the remaining values of $W(\varphi)$. Also, it decreases for the first value and increases for the other two with decrease in λ.

2.2. Closed Universe ($k = 1$). In this case, (17) gives two roots φ^- and φ^+ which are solved numerically for the three forms of $W(\varphi)$. The plots of H, ω^{eff}, q, and $V(\varphi)$ for φ^- are shown in Figures 4–6. The plots of H show standard behavior for all forms of $W(\varphi)$ while decrease in λ increases H. The plots of ω^{eff} indicate that for all $W(\varphi)$, it is -1 or corresponds to ΛCDM as time increases. The change in λ does not affect ω^{eff} for exponential form of $W(\varphi)$, while it initially decreases with decrease in λ for polynomial form and increases with decrease in λ for trigonometric case but it is equal to -1 for all values of λ as time increases.

The graphs of q in this case indicate an accelerated expansion which approaches to de-sitter expansion for late times. Also, increase in λ increases q for second and third models of scalar field, while for first model q remains constant for all values of λ. The plots for scalar field potential show that it is negative and decreasing for exponential as well as trigonometric forms while positive and decreasing for the polynomial expression. The decrease in λ implies an increase in $V(\varphi)$ for first and third values of $W(\varphi)$ but it has an opposite effect for second value. The behavior of H, ω^{eff}, and $V(\varphi)$ for φ^+ is similar to φ^-. For φ^+, the initial condition and model parameter remain unchanged, while the sign of b_i ($i = 1, 2, 3$) is opposite.

2.3. Open Universe ($k = -1$). In this case, the graphs are given in Figures 7–9. The Hubble parameter has increasing behavior which approaches to constant when the model approaches to ΛCDM for all the three forms of $W(\varphi)$. For

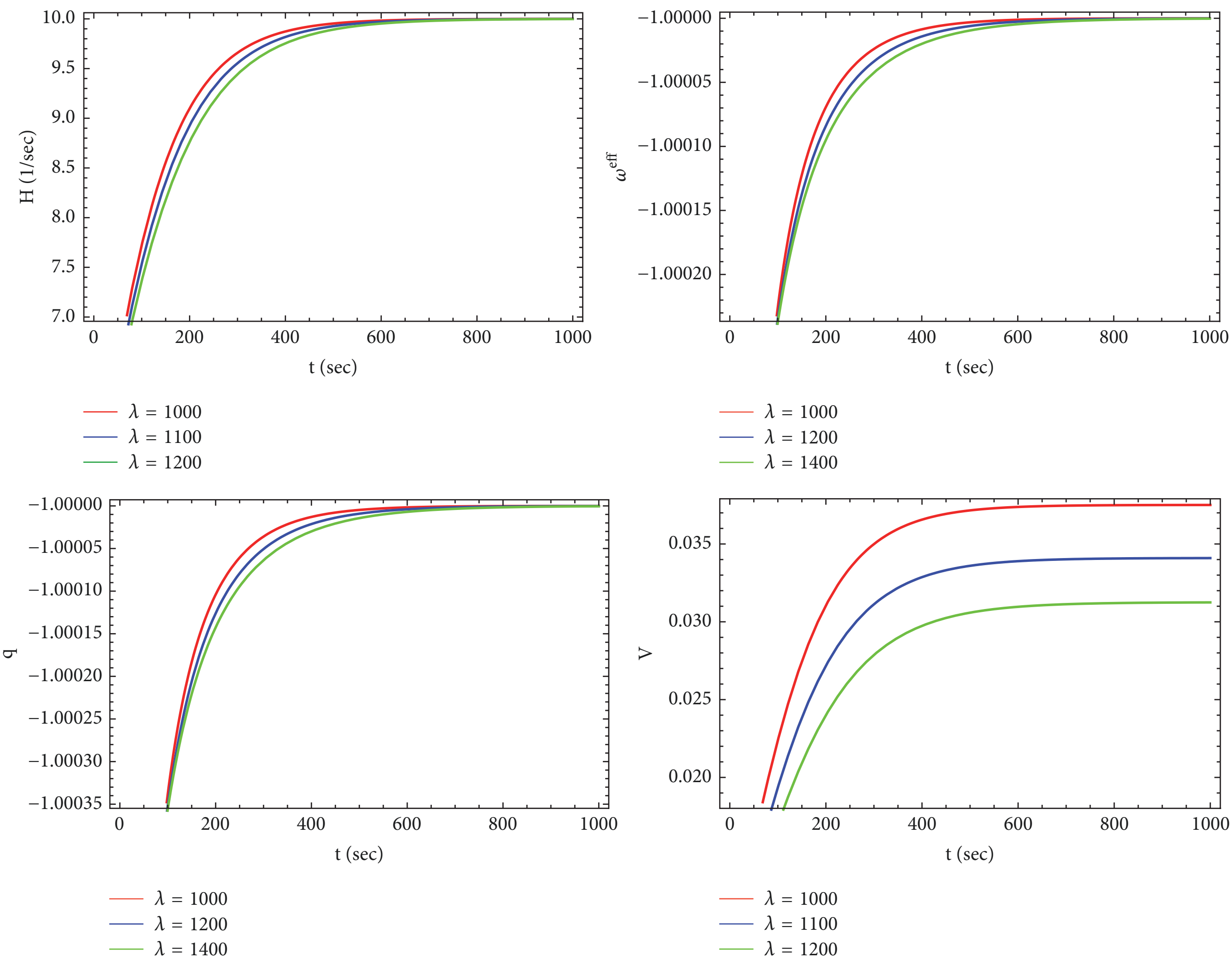

FIGURE 9: Plots of H, ω^{eff}, q, and V versus t for $W(\varphi^-) = b_3 \sin \varphi^-$, $b_3 = 10(1/sec)$, and $\varphi^-(0) = 0.5$ when $k = -1$.

all forms, ω^{eff} initially lies in phantom era and for later times it approaches -1. The behavior of q indicates that the expansion rate is slowing down. The scalar field potential is positive and decreasing for exponential case while positive and increasing for the remaining forms. The effect of model parameter is also observed in each graph. All plots for φ^+ have the same behavior as for φ^- under the conditions defined in the previous case.

3. Concluding Remarks

This paper investigates the cosmological behavior of FRW universe model in the background of $f(R, T^\varphi)$ gravity and in the absence of matter. We studied flat ($k = 0$), spherical ($k = 1$), and hyperbolic ($k = -1$) universe models assuming different values of Hubble parameter as a function of scalar field φ. It is found that, in flat universe, our model corresponds to ΛCDM for exponential form of Hubble parameter while for other two forms, it represents phantom phase in the beginning and then ΛCDM for late times. For the closed universe, quintessence phase is shown at early times and ΛCDM model for late times for all forms of $W(\varphi)$. In closed universe the polynomial and trigonometric expressions of $W(\varphi)$ described the stages of stiff fluid, radiation-dominated phase, matter-dominated era, quintessence, and de-Sitter expansion. In open universe scenario, our model initially falls in phantom phase and then is analogous to ΛCDM for all values of $W(\varphi)$. This is the main significance of our model that it can characterize the standard model for early as well as late time.

The deceleration parameter depicts that the rate of expansion is growing for closed universe, while it is slowing down for open universe. In case of flat universe, it is constant for exponential value and for remaining expressions of $W(\varphi)$, q has the same behavior as for open universe. The potential of scalar field has positive as well as negative values for different cases. It is important to note that when $V(\varphi)$ is increasing negatively (Figure 4), the corresponding ω^{eff} approaches -1 much earlier than other cases. The graphical analysis indicates different effects of the model parameter for different cases. It is interesting to mention here that ω^{eff} and q remain the same with varying λ for $k = \pm 1$

when $W(\varphi)$ is in exponential form. In view of the above discussion, we conclude that the closed universe scenario provides consistent results with an expanding universe in the context of $f(R,T^{\varphi})$ gravity.

Finally, we compare our results for the flat universe model with the paper [27], in which the authors used the differential equation $\dot{\varphi} = -W_{\varphi}$ obtained from GR field equations [25]. They found that the model $f(R,T^{\varphi}) = -R/4 + \lambda T^{\varphi}$ yields $-1 < \omega^{eff} < 1/3$ which does not correspond to the phantom era. However, we have used the first-order formalism in its true spirit, i.e., assuming Hubble parameter as a function of scalar field and using modified field equations to obtain the differential equation (17). We have found that this model characterizes ΛCDM for exponential H and represents ΛCDM as well as phantom phase for other two forms of $W(\varphi)$.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank the Higher Education Commission, Islamabad, Pakistan, for its financial support through the *Indigenous Ph.D. 5000 Fellowship Program Phase-II, Batch-III*.

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