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Anisotropic Cosmological Model with Domain Wall and Bulk Viscosity in Second Self-Creation Theory

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Abstract **Review Article**

In the present article, we have studied a spatially homogeneous and anisotropic Bianchi Type-V cosmological model in the framework of Barber's second self-creation theory of gravitation in the presence of a thick domain wall coupled with a bulk viscous fluid. The exact solutions of non-linear field equations are obtained by considering Berman's spatial law of variation of the Hubble parameter. Also, some physical and kinematical parameters of the models are discussed and presented graphically.
Keywords: Bianchi type-V metric, Barber's second self-creation theory, thick domain wall, bulk viscous fluid.

1. INTRODUCTION

The recent discovery of an accelerating expansion of the cosmos has piqued researchers' interest. Einstein's general theory of relativity, the fundamental theory of gravitation, provides a thorough grasp of the fundamentals and significance of astrophysical concepts, including high-energy astrophysics, gravitational-wave astronomy, and cosmic phenomena. But it does not validate Mach's principle observed by Einstein himself. Numerous alternative theories were developed as a result of modifications to Einstein's general theory of relativity. Among them, in 1982, Barbar [1] proposed two self-creation theories derived from two sets of general relativity, encompassing matter and scalar fields.

The first Barber's self-creation theory is a modified Brance-Dicke theory that is unsatisfactory because it violates the equivalence principle. Second self-creation theory of Barber's is a modification of general relativity that incorporates continuous creation and is with observational bounds, making it a variable G-theory in which the scalar field ϕ acts as a reciprocal of the gravitational constant by dividing the matter tensor rather than gravitating. Additionally, the trace of the energy-momentum tensor is coupled to the scalar field. The field equations of Barber's second self-creation theory of gravitation are defined by

$$R_{ij}-\frac{1}{2}g_{ij}R=-8\pi\phi^{-1}T_{ij}, \tag{1}$$

and $$\Box\phi=\phi^{k}_{;k}=\frac{8\pi}{3}\mu T \tag{2}$$

where, T_{ij} is the energy-momentum tensor, ϕ is the Barber's scalar function of time and μ is the coupling constant.

Several researchers have examined a number of features using different space-time in order to consider the consistency and stability of Barber's second self-creation theory, including the Anisotropic Bianchi type-I cosmological model using polytropic dark energy investigated by Katore S. D. and Kapse D. V. [2], Rao V. U. M. and Prasanthi U. D. [3]. constructed Bianchi type-V cosmological model with matter and anisotropic dark energy in second self-creation theory [3]. Bhaskara Rao M. P. V. V. *et al.,* examined spatially homogeneous and anisotropic Bianchi type-V space-time with bulk viscous cosmic string in the second self-creation theory of gravity [4]. The stability of the Bianchi type-II cosmological model in the presence of a macroscopic body was studied by Nimkar A. S. and Hadole S. [5]. Pawar D. D. and Solanke Y.

S. [6]. discussed the Bianchi type-IX cosmological model in the presence of magnetised anisotropic dark energy within the framework of Barber's second self-creation theory [6]. Tade S. D. *et. al.* [7], Ashtankar N. K. *et al.* [8], Santhi M. V. *et al.,* [9], Rautkar D. and Raut V. B. [10], Advani P. and Jain N. [11] are some of the authors who investigated different aspects of numerous cosmological models in Barber's second self-creation theory.

One of the greatest and most important cosmological mysteries is the creation of our world and at the early stage of the evolution of the universe, it was a challenging problem to know the exact physical situation. However, the spontaneous breaking of discrete symmetry during the early universe's phase transition, topological defects are significant from the perspective of the universe. Hill C. T. et.al. [12] explained that domain walls created during a phase transition following the recombination of matter and radiation are responsible for the formation of galaxies. Stable topological defects include cosmic strings, domain walls and monopoles. Of all these the most interesting cosmic structure is the domain wall. Many researchers have studied the gravitational effects of domain walls in various theories of gravity such as a plane symmetric domain wall in the presence of bulk viscous fluid in the framework of Lyra geometry investigated by Pradhan A. [13]. Bianchi type-III cosmological model with cosmic string and domain wall in *f(R,T)* gravity explored by Mete V. G. *et. al.* [14]. Katore S. D. *et. al.* constructed the two models FRW and an axially symmetric space-time in *f(R,T)* gravity in the presence of thick domain walls as source of matter [15]. Using domain walls as a source, Hatkar S. P. *et. al.* examined Bianchi type VI0 in the context of *f(R,T)* gravity [16]. Pawar D.D. *et. al.* studied the FRW cosmological model in Fractal cosmology with domain wall as a source [17].

Motivated by the analysis and discussion above, we have defined the metric and derived field equations in Section 2. Section 3 contains solutions to the field equations. Physical and kinematical parameters are discussed in Section 4. Section 5 presents the results and comments. Section 6 summarises the findings.

2. The Metric and Field Equations:

We consider the anisotropic Bianchi type-V space-time, which is in the form

$$ds^2 = dt^2 - A^2 dx^2 - e^{2mx}\left(B^2 dy^2 + C^2 dz^2\right) \tag{3}$$

where *A, B* and *C* are functions of time *'t'* only, *(x,y,z,t)* are the cartesian coordinates, and *m* is constant.

The energy-momentum tensor for domain walls coupled with bulk viscous is

$$T_{ij} = \left(g_{ij} + \omega_i \omega_j\right)\rho + \bar{p}\,\omega_i\,\omega_j\,, \tag{4}$$

$$\text{and,}\quad \bar{p} = p - 3\xi H, \qquad \omega_i \omega^j = -1. \tag{5}$$

where, $\bar{p}$ is the effective pressure, *p* is the pressure, ρ is energy is energy, ξ is the bulk viscous coefficient, *H* is the Hubble parameter, and $\omega^i = (0,0,0,-1)$ is the four-velocity vector of the distribution.

In the co-moving coordinate system, the components of the energy-momentum tensor are obtained from (4) and (5), and we have

$$T_1^1 = T_2^2 = T_3^3 = \rho,\ T_4^4 = -\bar{p} \quad \text{and} \quad T = 3\rho - \bar{p} \tag{6}$$

For the metric (3), the Barber's field equations from (1) and (2) with the help of (6) are obtained as follows

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} - \frac{m^2}{A^2} = 8\pi\phi^{-1}\rho\,, \tag{7}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} - \frac{m^2}{A^2} = 8\pi\phi^{-1}\rho\,, \tag{8}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{m^2}{A^2} = 8\pi\phi^{-1}\rho\,, \tag{9}$$

$$\frac{\dot{A}\dot{B}}{AB} + \frac{\dot{B}\dot{C}}{BC} + \frac{\dot{A}\dot{C}}{AC} - \frac{3m^2}{A^2} = -8\pi\phi^{-1}\bar{p}\,, \tag{10}$$

$$\ddot{\phi} + \dot{\phi}\left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right) = \frac{8}{3}\pi\mu\left(3\rho - \bar{p}\right)\,. \tag{11}$$

Where an overhead dot represents the differentiation with respect to time '*t*'.

Some Kinematical parameters are defined as follows

3. Solutions of the field equations:

To obtain the required solution, the quadrature method is used. For this, subtracting equations (7) from (8), (7) from (9) and (8) from (9), we obtain

$$\frac{d}{dt}\left(\frac{\dot{A}}{A}-\frac{\dot{B}}{B}\right)+\left(\frac{\dot{A}}{A}-\frac{\dot{B}}{B}\right)\frac{\dot{V}}{V}=0\ , \tag{12}$$

$$\frac{d}{dt}\left(\frac{\dot{A}}{A}-\frac{\dot{C}}{C}\right)+\left(\frac{\dot{A}}{A}-\frac{\dot{C}}{C}\right)\frac{\dot{V}}{V}=0\ , \tag{13}$$

$$\frac{d}{dt}\left(\frac{\dot{B}}{B}-\frac{\dot{C}}{C}\right)+\left(\frac{\dot{B}}{B}-\frac{\dot{C}}{C}\right)\frac{\dot{V}}{V}=0\ . \tag{14}$$

Integrating equations (12)-(14) twice and simplifying them, we obtain

$$\frac{A}{B}=l_1\exp\left(m_1\int\frac{dt}{V}\right)\ , \tag{15}$$

$$\frac{A}{C}=l_2\exp\left(m_2\int\frac{dt}{V}\right)\ , \tag{16}$$

$$\frac{B}{C}=l_3\exp\left(m_3\int\frac{dt}{V}\right)\ . \tag{17}$$

Where, $l_1, l_2\, l_3$ and $m_1, m_2\, m_3$ are constants of integration. Simplifying equations (15)-(17), we can write the metric potentials *A, B,* and *C* explicitly as

$$A=a\,k_1\exp\left(d_1\int\frac{dt}{V}\right), \tag{18}$$

$$B=a\,k_2\exp\left(d_2\int\frac{dt}{V}\right), \tag{19}$$

$$C=a\,k_3\exp\left(d_3\int\frac{dt}{V}\right)\ . \tag{20}$$

where, $k_1=\left(l_1\,l_2\right)^{1/3}$, $k_2=\left(l_1^{-1}\,l_3\right)^{1/3}$, $k_3=\left(l_2\,l_3\right)^{-1/3}$, $d_1=\frac{m_1+m_2}{3}$, $d_2=\frac{m_3-m_1}{3}$, $d_3=-\frac{\left(m_2+m_3\right)}{3}$ which satisfy the relation $k_1\,k_2\,k_3=1$ and $d_1+d_2+d_3=0$. Here, *a* represents the average scale factor. From above, the field equations (7) to (10) are a system of four independent equations with six unknowns *A, B, C,* $\rho, \overline{p}$ and ϕ So to find the determinate solution, we use the following two constraints

i) The power law relation between the average scale factor *'a'* and the scalar field 'ϕ' [18], given by

$$\phi=r\,a^u\ , \tag{21}$$

where *r* and *u* are constants.

ii) We consider a constant negative deceleration parameter defined by

$$q=-\frac{a\ddot{a}}{\dot{a}^2}=\text{Constant.} \tag{22}$$

In this case, the constant is assumed to be negative, i.e., the universe model accelerates.

On simplifying (22), it yields

$$a\left(t\right)=\left(b_1t+b_2\right)^{1/(1+q)}\ , \tag{23}$$

Where b_1 and b_2 are constants of integration, and the equation shows that $1+q>0$ is the expansion condition.

The value of the scalar field is obtained by substituting (23) in (21). We get

$$\phi\left(t\right)=r\left(b_1t+b_2\right)^{u/(1+q)} \tag{24}$$

From equations (18) – (20) and (23), the metric potential becomes

$$A = k_1 \left(b_1 t + b_2\right)^{\frac{1}{1+q}} \exp\left(\frac{d_1(1+q)}{b_1(q-2)}\left(b_1 t + b_2\right)^{\frac{q-2}{1+q}}\right),$$

$$B = k_2 \left(b_1 t + b_2\right)^{\frac{1}{1+q}} \exp\left(\frac{d_2(1+q)}{b_1(q-2)}\left(b_1 t + b_2\right)^{\frac{q-2}{1+q}}\right),$$

$$C = k_3 \left(b_1 t + b_2\right)^{\frac{1}{1+q}} \exp\left(\frac{d_3(1+q)}{b_1(q-2)}\left(b_1 t + b_2\right)^{\frac{q-2}{1+q}}\right).$$

With the above values of *A, B,* and *C,* equation (3) becomes

$$\begin{aligned} ds^2 &= dt^2 - k_1^2 \left(b_1 t + b_2\right)^{\frac{2}{1+q}} \exp\left(\frac{2d_1(1+q)}{b_1(q-2)}\left(b_1 t + b_2\right)^{\frac{q-2}{1+q}}\right) dx^2 - \\ & e^{2mx}\left(b_1 t + b_2\right)^{\frac{2}{1+q}}\left[k_2^2 \exp\left(\frac{2d_2(1+q)}{b_1(q-2)}\left(b_1 t + b_2\right)^{\frac{q-2}{1+q}}\right) dy^2 + k_3^2 \exp\left(\frac{2d_3(1+q)}{b_1(q-2)}\left(b_1 t + b_2\right)^{\frac{q-2}{1+q}}\right) dz^2\right] \end{aligned} \tag{25}$$

4. Some Physical and Kinematical Parameters:

The volume of the metric is

$$V = a^3 = \left(b_1 t + b_2\right)^{\frac{3}{1+q}}, \tag{26}$$

The Hubble parameter for the scale factor (23) is given by

$$H = \frac{\dot{a}}{a} = \frac{b_1}{(1+q)}\left(b_1 t + b_2\right)^{-1}, \tag{27}$$

The expansion scalar is

$$\theta = 3H = \frac{3b_1}{(1+q)}\left(b_1 t + b_2\right)^{-1}, \tag{28}$$

The shear scalar

$$\begin{aligned} \sigma^2 &= \frac{1}{2}\sigma_{ij}\sigma^{ij} = \frac{1}{2}\left[\sum_{i=1}^{3} H_i^2 - \frac{1}{3}\theta^2\right] \\ &= \frac{1}{2}\left(d_1^2 + d_2^2 + d_3^2\right)^2 \left(b_1 t + b_2\right)^{\frac{-6}{1+q}} + \frac{b_1^2}{(1+q)^2}\left(b_1 t + b_2\right)^{-2}, \end{aligned} \tag{29}$$

The anisotropic parameter is

$$\Delta = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i - H}{H}\right)^2 = \frac{1}{3}\left[\frac{(1+q)^2}{b_1^2}\left(d_1^2 + d_2^2 + d_3^2\right)\left(b_1 t + b_2\right)^{\frac{2(-2+q)}{1+q}}\right]. \tag{30}$$

From equation (7), the energy density for the given model is

$$\rho = \frac{1}{8\pi}\left[\begin{aligned} & r\left(d_2^2 + d_3^2 + d_2 d_3\right)\left(b_1 t + b_2\right)^{\frac{u-6}{1+q}} + \frac{(1-2q) r b_1^2}{(1+q)^2}\left(b_1 t + b_2\right)^{\frac{u-2-2q}{1+q}} \\ & - \frac{m^2 r}{k_1^2}\left(b_1 t + b_2\right)^{\frac{u-2}{1+q}} \exp\left(\frac{-2d_1(1+q)}{b_1(q-2)}\left(b_1 t + b_2\right)^{\frac{q-2}{1+q}}\right) \end{aligned}\right], \tag{31}$$

From equation (10), the effective pressure is obtained as

$$\bar{p} = -\frac{r}{8\pi}\left[\begin{array}{l}\left(d_1d_2+d_2d_3+d_1d_3\right)\left(b_1t+b_2\right)^{\frac{u-6}{1+q}}+\frac{3b_1^{\,2}}{\left(1+q\right)^2}\left(b_1t+b_2\right)^{\frac{u-2-2q}{1+q}} \\ \qquad -3\frac{m^2}{k_1^{\,2}}\left(b_1t+b_2\right)^{\frac{u-2}{1+q}}\exp\left(\frac{-2d_1\left(1+q\right)}{b_1\left(q-2\right)}\left(b_1t+b_2\right)^{\frac{q-2}{1+q}}\right)\end{array}\right], \tag{32}$$

Since, $\bar{p} = p - 3\xi H$. So, the pressure in the direction perpendicular to the wall's plane is

$$p = -\frac{r}{8\pi}\left[\begin{array}{l}\left(d_1d_2+d_2d_3+d_1d_3\right)\left(b_1t+b_2\right)^{\frac{u-6}{1+q}}+\frac{3b_1^{\,2}}{\left(1+q\right)^2}\left(b_1t+b_2\right)^{\frac{u-2-2q}{1+q}} \\ \qquad -3\frac{m^2}{k_1^{\,2}}\left(b_1t+b_2\right)^{\frac{u-2}{1+q}}\exp\left(\frac{-2d_1\left(1+q\right)}{b_1\left(q-2\right)}\left(b_1t+b_2\right)^{\frac{q-2}{1+q}}\right)\end{array}\right]+3\xi H . \tag{33}$$

By choosing the coefficient of bulk viscosity [19-23], the following ρ -dependent expansion is observed significantly.

$$\xi\left(t\right) = \xi_0\,\rho^{\beta} \tag{34}$$

Where, ξ_0 and β are constants. If $\beta = 1$, the radiative fluid is represented by equation (34). But when the value of β lying in the range $0 \le \beta \le \frac{1}{2}$ we obtain more realistic model [24]. We consider the following three cases $\left(\beta = 0, \frac{1}{2}, 1\right)$.

Case I: Solution for $\beta = 0$

When $\beta = 0$, Equation (34) reduces to a constant *i. e.* $\xi = \xi_0$. Hence, for this case equation (33) leads to

$$p = 3\xi_0 H - \frac{r}{8\pi}\left[\begin{array}{l}v_1\left(b_1t+b_2\right)^{\frac{u-6}{1+q}}+\frac{3b_1^{\,2}}{\left(1+q\right)^2}\left(b_1t+b_2\right)^{\frac{u-2-2q}{1+q}} \\ \qquad -3\frac{m^2}{k_1^{\,2}}\left(b_1t+b_2\right)^{\frac{u-2}{1+q}}\exp\left(\frac{-2d_1\left(1+q\right)}{b_1\left(q-2\right)}\left(b_1t+b_2\right)^{\frac{q-2}{1+q}}\right)\end{array}\right] \tag{35}$$

Case II: Solution for $\beta = \frac{1}{2}$.

When $\beta = \frac{1}{2}$, equation (34) reduces to $\xi = \xi_0 \rho^{1/2}$ so the equation (33) gives,

$$\begin{aligned}p = &-\frac{r}{8\pi}\left[\begin{array}{l}v_1\left(b_1t+b_2\right)^{\frac{u-6}{1+q}}+\frac{3b_1^{\,2}}{\left(1+q\right)^2}\left(b_1t+b_2\right)^{\frac{u-2-2q}{1+q}} \\ \qquad -3\frac{m^2}{k_1^{\,2}}\left(b_1t+b_2\right)^{\frac{u-2}{1+q}}\exp\left(\frac{-2d_1\left(1+q\right)}{b_1\left(q-2\right)}\left(b_1t+b_2\right)^{\frac{q-2}{1+q}}\right)\end{array}\right] \\ &+\frac{3r\xi_0 H}{8\pi}\left[\begin{array}{l}v_2\left(b_1t+b_2\right)^{\frac{u-6}{1+q}}+\frac{\left(1-2q\right)b_1^{\,2}}{\left(1+q\right)^2}\left(b_1t+b_2\right)^{\frac{u-2-2q}{1+q}} \\ \qquad -\frac{m^2}{k_1^{\,2}}\left(b_1t+b_2\right)^{\frac{u-2}{1+q}}\exp\left(\frac{-2d_1\left(1+q\right)}{b_1\left(q-2\right)}\left(b_1t+b_2\right)^{\frac{q-2}{1+q}}\right)\end{array}\right]^{\frac{1}{2}}\end{aligned} \tag{36}$$

Case III: Solution for $\beta = 1$.

When $\beta = 1$, Equation (34) reduces in the form $\xi = \xi_0\rho$. Hence, equation (33) becomes

$$p = -\frac{r}{8\pi}\left[\begin{array}{l}\left(v_1-3\xi_0 H v_2\right)\left(b_1t+b_2\right)^{\frac{u-6}{1+q}}+\frac{3b_1^{\,2}}{\left(1+q\right)^2}\left(1-\left(1-2q\right)\xi_0 H\right)\left(b_1t+b_2\right)^{\frac{u-2-2q}{1+q}} \\ \qquad -\frac{3m^2}{k_1^{\,2}}\left(1-\xi_0 H\right)\left(b_1t+b_2\right)^{\frac{u-2}{1+q}}\exp\left(\frac{-2d_1\left(1+q\right)}{b_1\left(q-2\right)}\left(b_1t+b_2\right)^{\frac{q-2}{1+q}}\right)\end{array}\right] \tag{37}$$

In the above equations, $\left(d_1d_2+d_2d_3+d_1d_3\right)$ and $\left(d_2^{\,2}+d_3^{\,2}+d_2d_3\right)$ are represented by v_1 and v_2 respectively.

5. Observations and Results:

Barber's scalar function ϕ is an increasing function of time as shown in Figure 1. From figure 2, it is observed that the spatial volume begins at a constant value as time approaches zero and continuously expands with the progression of time. This shows that when $t \to 0$, Universe evolves with zero volume, and when $t \to \infty$ the spatial volume $V \to \infty$ *i.e.,* it expands with time [25].

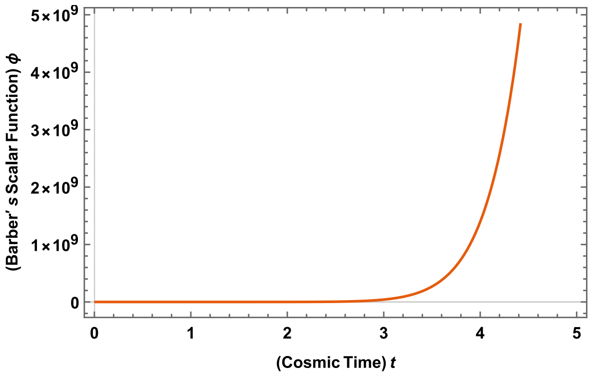

Fig. 1. The plot of a scalar function ϕ versus cosmic time *t*.

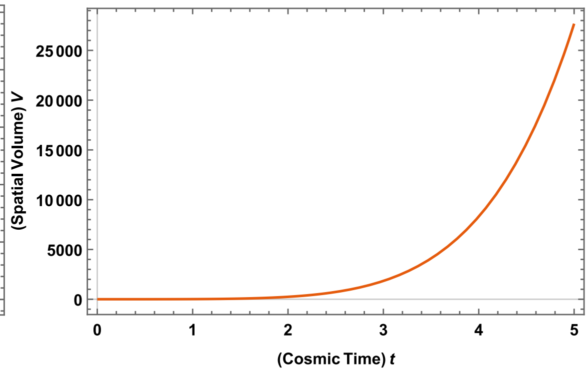

Fig. 2. The Plot of Spatial Volume (V) versus cosmic time *t*.

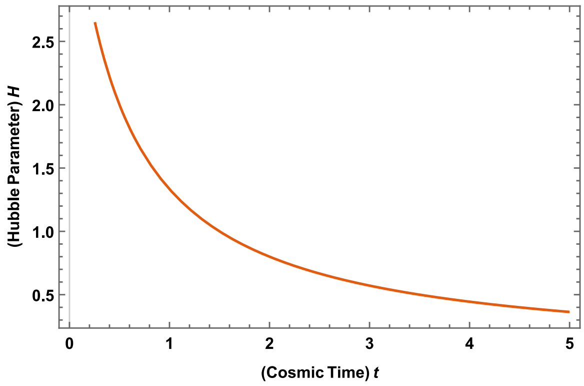

Fig.3 The plot of Hubble parameter (H) Cosmic time *t*.

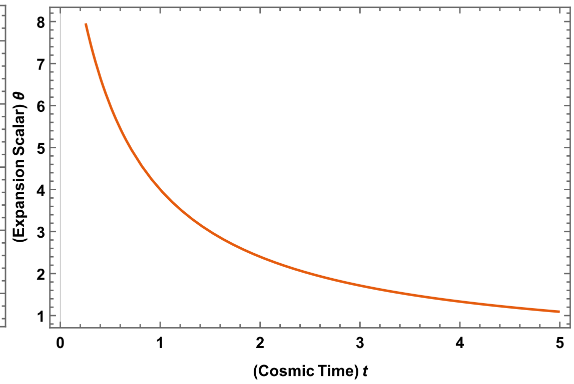

Fig.4. The plot of Expansion scalar θ versus Cosmic time *t*.

Figures 3 and 4 represent the Hubble parameter and the expansion scalar. Initially, both have constant values, and as time increases, the behaviour of the Hubble Parameter and the expansion scalar both decrease and approach zero after infinite time. Therefore, we observed that our model continues to expand at a slower rate, which is in good agreement with current observations of the universe [26-28].

Figure 5 depicts the shear scalar in the cosmological model is positive decreasing function of cosmic time and converging towards a small positive constant value. Figure 6 shows that initially, the anisotropy parameter is constant and $\Delta \to 0$ with increasing time.

From Figure 7, it is observed that initially the density of the model is zero, and it increases with increasing time. This means that the energy density continues to increase with time. Figure 8 explains that the variation of pressure with respect to cosmic time shows that pressure falls as cosmic time grows, implying an accelerating cosmos caused by negative pressure.

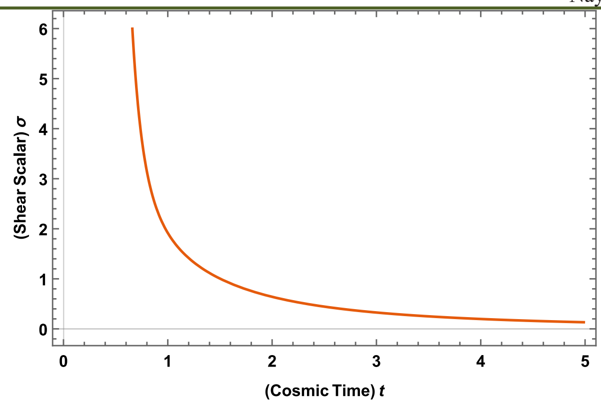

Fig. 5. The plot of Shear scalar σ versus Cosmic time *t*.

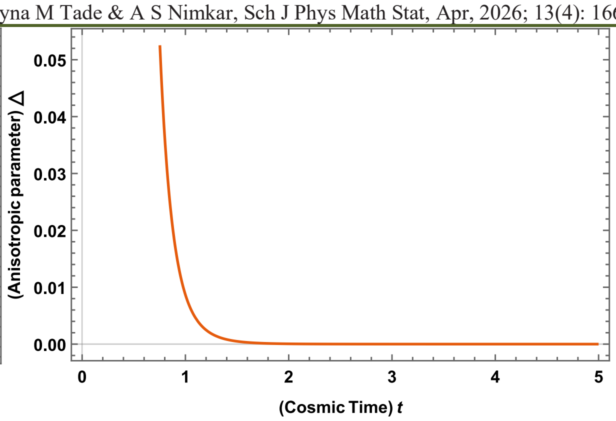

Fig.6. The plot of Anisotopy parameter Δ Cosmic time *t*.

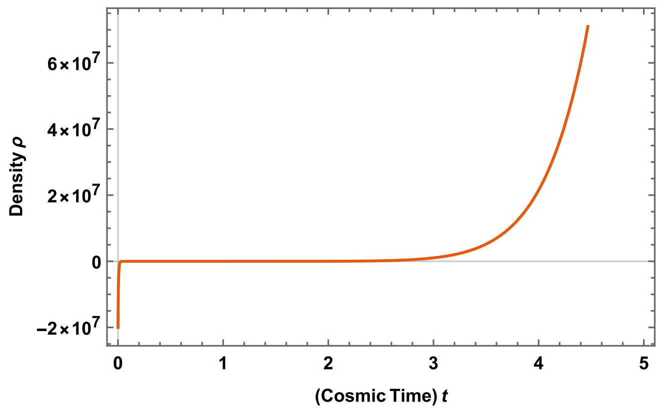

Fig. 7. The plot of Energy density ρ versus Cosmic time *t*.

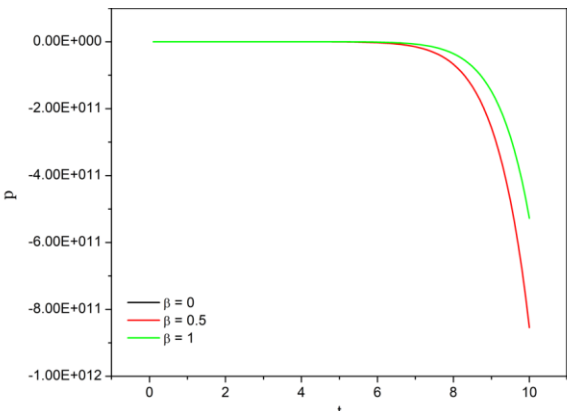

Fig. 8. The plot of Pressure p versus Cosmic time *t*.

6. CONCLUSION

In the present work, we have examined the Bianchi type-V cosmological model within the framework of Barber's second self-creation theory, using bulk viscosity combined with the thick domain wall as a matter source. We have used Berman's spatial law of variation of the Hubble parameter for finding solutions of the field equations. Three models for $\beta = 0, \frac{1}{2} \& 1$ have been. According to the above findings, the bulk viscosity coefficient has an impact on the pressure of the domain wall but does not influence the domain wall's density or effective pressure. The value of the deceleration parameter lies in $-1 \leq q \leq 0$ showing an accelerating phase. It is found that the constructed universe is anisotropic, singularity-free, expanding at a decreasing rate with increasing time, and maintaining shear until infinite time, all of which are consistent with recent research. Singularity is seen in the Barber's scalar field as cosmic time approaches infinity. Hence, the model's behaviour agrees with present cosmological findings.

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