



An In-Depth Analysis of Wavelet Transform Performance in Solving the Burgers–Fisher Equation: A Foundation for Improving Accuracy and Efficiency in Numerical Computation

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تحليل معمق لأداء تحويل المويجات في حل معادلة " بورجرز-فيشر ": ركيزة لتحسين الدقة والكفاءة في الحسابات العددية

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Received: July 29, 2026

Accepted: September 30, 2026

Published: October 05, 2026



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Abstract.

The Burgers–Fisher equation is a nonlinear partial differential equation with a hybrid hyperbolic–parabolic nature and arises in many areas of applied and physical sciences, including fluid mechanics, gas dynamics, and reaction–diffusion processes. In this study, the effectiveness of the Haar wavelet transform and the Daubechies (DB8) wavelet transform is investigated for obtaining numerical solutions of the Burgers–Fisher equation. Numerical experiments demonstrate that both wavelet-based approaches provide efficient approximations and satisfactory convergence behavior. However, the Daubechies (DB8) transform achieves significantly higher accuracy and better numerical stability than the Haar transform. The obtained results show that the DB8 wavelet produces errors several orders of magnitude smaller than those generated by the Haar wavelet, yielding excellent agreement with the exact solution. This improvement is attributed to the smoother basis functions and higher vanishing moments of the DB8 wavelet, which allow a more effective representation of the nonlinear characteristics of the Burgers–Fisher equation. Therefore, the proposed wavelet-based approach, particularly the DB8 transform, is shown to be a reliable and accurate technique for solving nonlinear partial differential equations.

Keywords: Wavelet Transform, Burgers–Fisher Equation, Daubechies (DB8), Haar Wavelet Transform.

المخلص

معادلة برجرز-فيشر هي معادلة تفاضلية جزئية غير خطية ذات طبيعة هجينة بين الزخم والتشتت، وتظهر في العديد من مجالات العلوم التطبيقية والفيزيائية، بما في ذلك ميكانيكا الموائع، ديناميكا الغازات، وعمليات التفاعل والانتشار. في هذه الدراسة، تم التحقيق في فعالية تحويل المويجات هار وتحويل المويجات داوبيشيز (DB8) للحصول على حلول عددية لمعادلة برجرز-فيشر. تظهر التجارب العددية أن كلا الطريقتين القائمتين على المويجات توفر تقريباً فعالاً وسلوك تقارب مرضٍ. ومع ذلك، يحقق تحويل داوبيشيز (DB8) دقة أعلى بكثير واستقراراً عددياً أفضل من تحويل هار. توضح النتائج المحصل عليها أن موجة DB8 تنتج أخطاءً أصغر بعدة مراتب من تلك الناتجة عن موجة هار، مما يؤدي إلى توافق ممتاز مع الحل الدقيق. يُعزى هذا التحسن إلى دوال الأساس الأكثر سلاسة ولحظات الزوال الأعلى لموجة DB8، والتي تسمح بتمثيل أكثر فعالية للخصائص غير الخطية لمعادلة برجرز-فيشر. لذلك، تم إثبات أن النهج المقترح القائم على المويجات، وبشكل خاص تحويل DB8، هو تقنية موثوقة ودقيقة لحل المعادلات التفاضلية الجزئية غير الخطية.

Introduction

Nonlinear partial differential equations arise from the mathematical modeling of many physical systems and appear in various fields of engineering and science. Numerical solutions to these equations, such as the Burgers–Fisher equation, have attracted considerable attention due to their applications in fluid dynamics, heat transfer, gas dynamics, traffic flow, and applied mathematics. Wavelet series have proven to be a fast, efficient, and highly accurate method for obtaining approximate solutions to nonlinear partial differential equations, and their use has increased significantly in recent years. These methods rely on two fundamental parameters: dilation and translation. The dilation parameter is used to compress the wavelet series solution, while the translation parameter determines the location of the solution within the $L^2(R)$ space. Wavelet-based approaches are known for their effectiveness in providing approximate solutions to PDEs in both regular and irregular domains. Moreover, wavelet functions are symmetric, which allows them to detect discontinuities in the equations and produce robust solutions that are resistant to noise. Thanks to the compact support property of wavelet functions, wavelet series solutions tend to converge faster than traditional approximation methods. In addition, the multiresolution analysis property of wavelets enables simultaneous access to both time and frequency information, an advantage not achievable with other approximation techniques for PDEs. In this work, the objective is to compare the approximate solutions obtained using Haar wavelets and Daubechies wavelets, with a particular focus on db8 wavelets, to demonstrate their superior accuracy compared to Haar wavelets.

Example 1

We consider the Burgers–Fisher equation, as presented, given by [Ali AlFayadh and Nawar Hazim (2017)]:

$$\frac{\partial u}{\partial t} + \alpha u \frac{\partial u}{\partial x} = \nu \frac{\partial^2 u}{\partial x^2} + \beta u(1 - u), \quad 0 \leq x \leq 1, \quad t \geq 0. \quad (1)$$

with the initial condition given by

$$u(x, 0) = \left(\frac{1}{2} - \frac{1}{2} \tanh\left(\frac{\alpha \gamma}{2(\gamma + 1)} x\right) \right)^{1/\gamma}, \quad (2)$$

$$u(0, t) = \left(\left(\frac{1}{2} + \frac{1}{2} \tanh\left(\frac{\alpha \gamma}{2(\gamma + 1)} \left(\frac{\alpha}{\gamma + 1} + \frac{\beta(\gamma + 1)}{\alpha} t \right) \right) \right) \right)^{1/\gamma}, \quad t \geq 0,$$

$$u(1, t) = \left(\frac{1}{2} + \frac{1}{2} \tanh\left[-\frac{\alpha \gamma}{2(\gamma + 1)} \left(1 - \left(\frac{\alpha}{\gamma + 1} + \frac{\beta(\gamma + 1)}{\alpha} t \right) \right) \right] \right)^{1/\gamma}, \quad t \geq 0. \quad (3)$$

Since the Burgers–Fisher equation with $\alpha = 0$ reduces to a simpler form that can be treated numerically, this study adopts the wavelet method using both Haar wavelets and Daubechies 8 (DB8) wavelets to obtain an approximate solution of the equation.

Accordingly, the boundary conditions can be expressed as follows:

$$u(x, t) = \left(\frac{1}{2} + \frac{1}{2} \tanh\left[-\frac{\alpha \gamma}{2(\gamma + 1)} \left(x - \left(\frac{\alpha}{\gamma + 1} + \frac{\beta(\gamma + 1)}{\alpha} t \right) \right) \right] \right)^{1/\gamma}, \quad t \geq 0. \quad (4)$$

This equation can be considered as an initial value problem. Therefore, we impose the following two conditions on Equation (1), so that we obtain [3 -4]

$$u(x, 0) = f(x), \quad 0 \leq x \leq 1, \quad (5)$$

$$u(0, t) = g_1(t), \quad t \geq 0, \quad (6)$$

$$u(1, t) = g_2(t), \quad t \geq 0. \quad (7)$$

We now divide the interval $[0, T]$ into N equal subintervals, each of length $\Delta t = \frac{T}{N}$.

These subintervals $t_s = (s - 1)\Delta t$ are used for the Haar wavelet discretization approach. To solve the problem using Haar wavelets, we assume that the governing equation can be written in the following form [7]

$$u(x, t) = \sum_{i=1}^{2M} a_i h_i(x) \quad (8)$$

It should be noted that the dot and prime symbols denote differentiation with respect to t and x , respectively. Accordingly, a_s is considered a constant over the interval $t \in [t_s, t_{s+1}]$.

We then integrate the equation, after rewriting it in the form of Equation (8), over this time subinterval. The resulting expression is subsequently integrated with respect to x over the interval $[0, x]$. Finally, differentiating the obtained expression with respect to t yields the following system of equations:

$$\ddot{u}(x, t) = (t - t_s) \sum_{i=1}^{2M} a_i h_i(x) + \ddot{u}(x, t_s) \quad (9)$$

$$u'(x, t) = u(x, t_s) \sum_{i=1}^{2M} a_i + u'(x, t_s) - u'(0, t) + u'(0, t_s) \quad (10)$$

$$u(x, t) = u(x, t_s) \sum_{i=1}^{2M} a_i + u(x, t_s) - u(0, t) + u'(0, t) - u'(0, t_s) + u(0, t_s) \quad (11)$$

$$u(x, t) = \sum_{i=1}^{2M} a_i + u(0, t_s) + u'(0, t_s) \quad (12)$$

We now use the boundary conditions (10)-(11) to obtain:

$$u(0, t) = g_1(t), \quad u(1, t) = g_2(t) \quad (13)$$

$$u'(0, t) = g'_1(t), \quad u'(1, t) = g'_2(t) \quad (14)$$

By setting $x = 1$ in Equations (13) and (14), and using the boundary conditions in Equations (14), we obtain the following results:

$$u'(0, t) - u'(0, t_s) = -(t - t_s) \sum_{i=1}^{2M} (g_1 + g_2 - g'_1 - g'_2 + g_1) \quad (15)$$

$$u'(0, t) = \sum_{i=1}^{2M} (g_1 + g_2 - g'_1) \quad (16)$$

It is well known that the wavelet collocation points are given by:

$$x_j = \frac{j - 0.5}{2M}, \quad j = 1, 2, \dots, 2M \quad (17)$$

Substituting Equations (18)-(21) into Equations (14)-(17) and taking

$t = t_s, t_{s+1}$, we obtain the following result:

$$\ddot{u}(x_j, t_s + 1) = \Delta t \sum_{i=1}^{2M} a_i h_i(x) + \ddot{u}(x_j, t_s) \quad (18)$$

$$u'(x_j, t_{s+1}) = \Delta t \sum_{i=1}^{2M} [a_i(u_j - u_{j-1}) + u'(x_j, t_s) + g_2(t_{s+1}) - g_1(t_{s+1}) - g_2(t_s)] \quad (19)$$

$$u(x_j, t_{s+1}) = \Delta t \sum_{i=1}^{2M} [a_i(u_j - u_{j-1}) + u(x_j, t_s) + (g_2(t_{s+1}) - g_2(t_s))] + (1 - u_j)(g_1(t_{s+1}) - g_1(t_s)) \quad (20)$$

$$u(x_j, t_{s+1}) = \sum_{i=1}^{2M} [a_i(u_j - u_{j-1}) + g_1(t_{s+1}) + (g_2(t_{s+1}) - g_1(t_{s+1}))] \quad (21)$$

Using the quasilinearization technique to linearize Equation (1), we obtain:

$$\sum_{i=1}^{2M} [a_i(u_j - u_{j-1}) + g_1(t_{s+1}) + (g_2(t_{s+1}) - g_1(t_{s+1}))] - \ddot{u}(x_j, t_{s+1})u(x_j, t_s) + u'(x_j, t_{s+1})u(x_j, t_s) \\ = u(x_j, t_{s+1})[1 - u(x_j, t_{s+1})] + u(x_j, t_s)u'(x_j, t_s) \quad (22)$$

This takes us to the different time levels t_s and t_{s+1} , through which the wavelet coefficients can be computed sequentially from Equation (19). This process is initiated using the initial condition (2). The obtained coefficients are then substituted into Equations (20)-(22), from which we obtain approximate numerical solutions at different time levels. We divided time into steps and analyzed the equation step by step to convert it into an algebraic system. When we put the equation into the form mentioned above, it was systematically transformed into a computable algebraic solution using Haar wavelet transform. We chose approximate linearity. This approach greatly simplified the solution process and maintained high numerical accuracy across different time levels, which we needed because there $u \frac{\partial u}{\partial x}$, $u(1-u)$ This is a non-linear limit, which makes the solution difficult and often indirect.

Results and Discussion

Daubechies Wavelet System

In a Daubechies wavelet framework, the sets of coefficients $\{a_k\}$ and $\{b_k\}$ are used to establish the refinement equations, which in turn fully characterize the scaling function $\phi(x)$ and the wavelet function $\psi(x)$. Consequently, the form of these functions directly influences the range of applications for which a given wavelet is suitable. These coefficient sequences $\{a_k\}$ and $\{b_k\}$ can be interpreted as filtering operators applied to the signal. In addition, wavelets are required to satisfy essential mathematical properties, most notably orthogonality, together with other desirable characteristics depending on the intended application. Such requirements impose constraints on the admissible values of the scaling and wavelet coefficients.

Orthonormality Condition

A wavelet system is said to be orthonormal when any pair of wavelets generated by translations and dilations satisfies the following condition:

$$\int_{-\infty}^{\infty} \psi_{k,l}(x) \psi_{m,n}(x) dx = \begin{cases} 1, & \text{if } k = m \text{ and } l = n, \\ 0, & \text{otherwise,} \end{cases}$$

where the function $\delta_{mn} \delta_{kl}$ represents the Kronecker delta, which ensures orthogonality and normalization of the wavelet basis functions.

Necessary and Sufficient Condition

For a wavelet system to achieve orthonormality, the integer shifts of the scaling function $\phi(x)$ must reproduce polynomials up to a certain degree K . In other words, for every integer k , one can find coefficients c_l such that

$$x^k = \sum_l c_l \phi(x - l).$$

Daubechies constructed a family of scaling functions with this reproduction property, characterized by having minimal compact support. A scaling function of order N , denoted by ϕ_N , is supported on the interval $[0, N - 1]$, while its associated wavelet ψ_N is supported on $\left[1 - \frac{N}{2}, \frac{N}{2}\right]$ and has $\frac{N}{2} - 1$ vanishing moments.

As a result, scaling functions of order N are capable of exactly representing polynomials of degree up to $\frac{N}{2} - 1$, but they cannot represent polynomials of higher degree.

Example 2

DWT using Db4 **Given signal:**

$$f = (5, 5, 6, 8, 12, 10, 6, 4)$$

Daubechies D4 filter coefficients (approximate values):

$$a = (0.483, 0.837, 0.224, -0.129), b = (-0.129, -0.224, 0.837, -0.483)$$

Step 1: Approximation coefficients

$$A1 = 0.483(5) + 0.837(5) + 0.224(6) - 0.129(8) \approx 6.912$$

$$A2 = 0.483(6) + 0.837(8) + 0.224(12) - 0.129(10) \approx 11.000$$

$$A3 = 0.483(12) + 0.837(10) + 0.224(6) - 0.129(4) \approx 14.994$$

$$A4 = 0.483(6) + 0.837(4) + 0.224(5) - 0.129(5) \approx 6.721$$

Step 2: Detail coefficients

$$D1 = -0.129(5) - 0.224(5) + 0.837(6) - 0.483(8) \approx -0.607$$

$$D2 = -0.129(6) - 0.224(8) + 0.837(12) - 0.483(10) \approx 2.648$$

$$D3 = -0.129(12) - 0.224(10) + 0.837(6) - 0.483(4) \approx -0.698$$

$$D4 = -0.129(6) - 0.224(4) + 0.837(5) - 0.483(5) \approx 0.100$$

Final DWT result:

$$DWT = (6.91, 11.00, 14.99, 6.72 \mid -0.61, 2.65, -0.70, 0.10)$$

Interpretation:

The Daubechies wavelet transform (DWT) decomposes the original signal into two parts:

1. The approximation coefficients
(6.91, 11.00, 14.99, 6.72)

represent the low-frequency components of the signal, capturing its overall trend or smooth behavior.

2. The detail coefficients
(-0.61, 2.65, -0.70, 0.10)

represent the high-frequency components, capturing rapid changes and local variations in the signal.

Thus, (DWT) reorganizes the information of the original signal without loss by decomposing it into approximation (coarse) and detail (fine) components.

The DWT maps a sequence of N observations into N wavelet coefficients. These coefficients are obtained through a sequence of filtering operations that capture both the magnitude and the time (or spatial) localization of the signal at different scales, i.e., across multiple frequency bands.

Using these coefficients, the original signal can be reconstructed with high accuracy, while also enabling efficient numerical approximation and multiresolution analysis. The decomposition process is performed in a hierarchical manner, starting from fine scales and progressively moving toward coarser scales. At each level, the scale increases, which improves the efficiency and flexibility of the multiresolution representation.

Numerical Results

Consider the Burger–Fisher equation (1) together with the initial and boundary conditions specified in (2) and (3), respectively, while the exact analytical solution is given in (4). The numerical experiments are performed using the parameters $\Delta x = 0.01$, $\Delta t = 0.01$, and $\alpha = 1$.

A comparison between the exact solution and the numerical results obtained via the DB8 wavelet approach is reported in Tables (1)-(3) for various values of x and t , along with the corresponding absolute errors. The obtained results demonstrate excellent agreement between the numerical and exact solutions, with absolute errors ranging approximately from 10^{-10} to 10^{-7} , which confirms the high accuracy of the DB8-based method. In addition, Tables (4)-(6) present the corresponding results obtained using the Haar wavelet method. Although the numerical solutions remain in close agreement with the exact solution, the associated absolute errors are noticeably larger compared to those produced by the DB8 method. Furthermore, it is observed that the absolute

error exhibits a slight growth as the time variable t increases. Nevertheless, the overall numerical results remain stable and maintain a strong agreement with the exact solution throughout the entire computational domain.

Table 1: Comparison between Ex and DB8 Solutions for Burger-Fisher Equation at $t = 0.02$

x_i	t_i	Exact Solution	DB8 Solution	Absolute error
0.01 0.02	0.02 0.02	4.102e-11 8.5332e-11	2.5886e-10 5.275e-10	2.1784e-10
0.03 0.04	0.02 0.02	2.5061e-10 5.067e-10	1.4835e-09 2.9089e-09	4.4217e-10
0.05	0.02	1.4259e-09	7.8138e-09	1.2329e-09
				2.4022e-09
				6.3924e-09

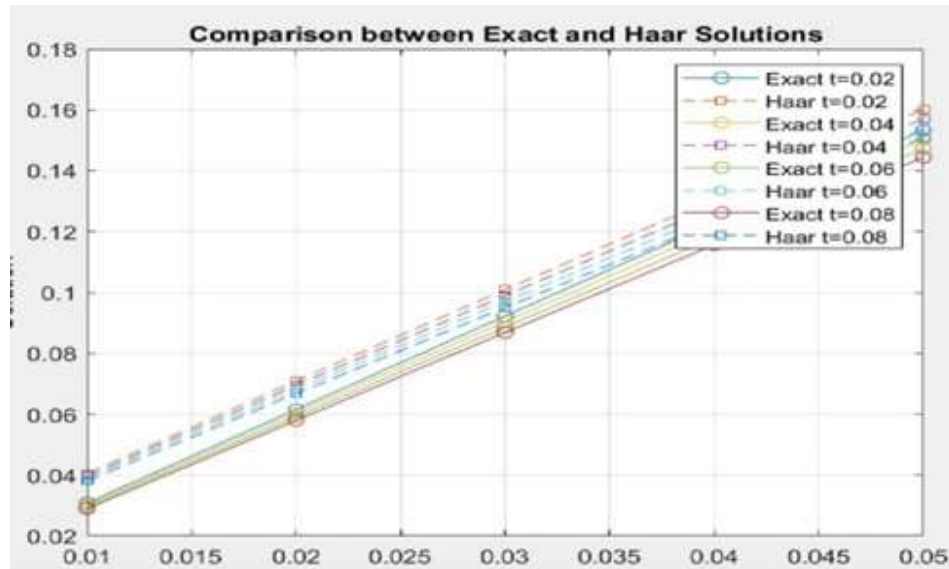


Figure 1: A comparison of the exact solution with the Haar wavelet-based approximation of the B–Fe is presented at several time instants, namely $t = 0.02, 0.04, 0.06$, and 0.08 , to evaluate the performance of the numerical method

Table 2: Comparison between Exact and DB8 Solutions for Burger-Fisher Equation at $t = 0.04$ and $t = 0.06$

x_i	t_i	Exact Solution	DB8 Solution	Absolute error
0.01	0.04	3.5748e-11	1.1897e-09	1.1539e-09
0.02	0.04	7.2639e-11	2.2974e-09	2.2247e-09
0.03	0.04	2.0626e-10	6.005e-09	5.7988e-09
0.04	0.04	4.0815e-10	1.1229e-08	1.0821e-08
0.05	0.04	1.1138e-09	2.8154e-08	2.704e-08
0.01	0.06	2.973e-11	4.4574e-09	4.4277e-09
0.02	0.06	5.9188e-11	8.2330e-09	8.171e-09
0.03	0.06	1.632e-10	2.0194e-08	2.0031e-08
0.04	0.06	3.1695e-10	3.6246e-08	3.5929e-08
0.05	0.06	8.42e-10	8.5576e-08	8.4734e-08

Table 3: Comparison between Exact and DB8 Solutions for Burger-Fisher Equation at $t = 0.08$

x_i	t_i	Exact Solution	DB8 Solution	Absolute error
0.01	0.08	2.3797e-11	1.4162e-08	1.4139e-08
0.02	0.08	4.6533e-11	2.5172e-08	2.5126e-08
0.03	0.08	1.2503e-10	5.8462e-08	5.8337e-08
0.04	0.08	2.3886e-10	1.0124e-07	1.01e-07
0.05	0.08	6.1979e-10	2.268e-07	2.2618e-07

Table 4: Comparison between Exact and Haar Solutions for Burger-Fisher Equation at $t = 0.02$ and $t = 0.04$

x_i	t_i	Exact Solution	Haar Solution	Absolute error
0.01 0.02 0.03 0.04 0.05	0.02	0.030789	0.04047 0.070869 0.10098 0.13078 0.16027	0.0096813
	0.02	0.061547		0.0093222
	0.02	0.092245		0.0087336
	0.02	0.12285		0.00793
	0.02	0.15334		0.0069311
0.01 0.02 0.03 0.04 0.05	0.04	0.030179	0.039669 0.069466 0.098979 0.12819 0.15709	0.0094896
	0.04	0.060328		0.0091377
	0.04	0.090418		0.0085607
	0.04	0.12042		0.007729
	0.04	0.1503		0.0067938

Table 5: Comparison between Exact and Haar Solutions for Burger-Fisher Equation at $t = 0.06$ and $t = 0.08$

x_i	t_i	Exact Solution	Haar Solution	Absolute error
0.01 0.02 0.03 0.04 0.05	0.06 0.06	0.029582	0.038883 0.068091 0.097019 0.12565 0.15393	0.0093017
	0.06 0.06	0.059134		0.0089567
	0.06 0.06	0.088628		0.0083912
	0.06	0.11803		0.007619
	0.06	0.14732		0.006593
0.01 0.02 0.03 0.04 0.05	0.08 0.08	0.028996	0.038113 0.066742 0.095098 0.12317 0.15093	0.0091175
	0.08 0.08	0.057963		0.0087794
	0.08 0.08	0.086873		0.008225
	0.08	0.1157		0.0074682
	0.08	0.14441		0.0065274

Table 6: Comparison between Exact and Haar Solutions for Burger-Fisher Equation at $t = 0.10$

x_i	t_i	Exact Solution	Haar Solution	Absolute error
0.01	0.10	0.028422	0.037359 0.065421 0.093215	0.008937
0.02	0.10	0.056815		0.0086055
0.03	0.10	0.085153		0.0080622

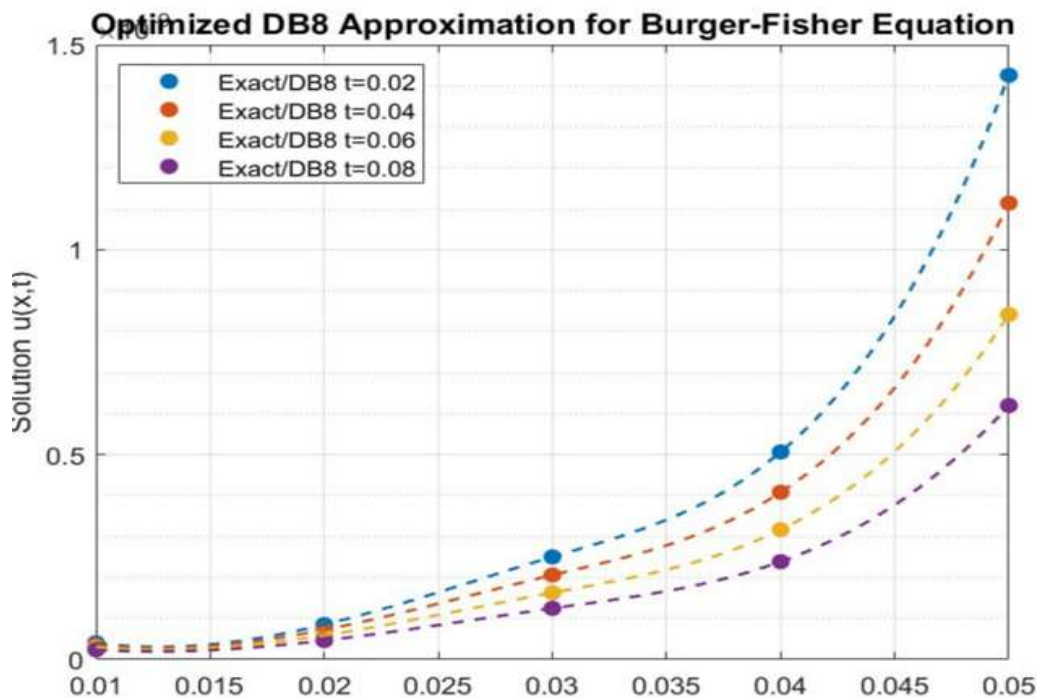


Figure 2: Optimized DB8 wavelet approximation of the B-Fe compared with the exact solution at different time levels $t = 0.02, 0.04, 0.06$, and 0.08 .

Conclusion

According to the numerical results reported in the previous tables, a noticeable distinction in both accuracy and stability can be identified between the Daubechies (DB8) and Haar wavelet methods. The DB8-based approximation consistently produces much smaller absolute errors over all spatial and temporal grid points when compared with the Haar-based approximation. In particular, the DB8 approach achieves errors on the order of 10^{-10} to 10^{-7} , which reflects an excellent agreement with the exact solution. On the other hand, the Haar wavelet method yields relatively larger deviations, with errors typically lying in the range of 10^{-3} to 10^{-2} . This improved accuracy of the DB8 wavelet is mainly due to its higher vanishing moments and smoother basis functions, which allow it to represent the nonlinear diffusion and reaction effects in the B–Fe more effectively. Accordingly, it can be concluded that the Daubechies (DB8) wavelet transform provides a more accurate and numerically stable approximation for the Burger–Fisher equation than the Haar wavelet. This confirms that higher-order smooth wavelet bases such as DB8 are more suitable for solving nonlinear partial differential equations where high precision and smooth solution behavior are required.

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