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Research Article

Exact Solutions of a Nonlinear Diffusion Equation with Absorption and Production

 Robert Conte* 

Université Paris-Saclay, ENS Paris-Saclay, CNRS, Centre Borelli, Cachan F-94235, France
 Department of Mathematics, The University of Hong Kong, Pokfulam Road, Hong Kong

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ABSTRACT

We provide closed form solutions for an equation which describes the transport of turbulent kinetic energy in the framework of a turbulence model with a single equation.

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1. INTRODUCTION

The Partial Differential Equation (PDE) [10]

$$\begin{aligned} x \text{ real}, t > 0: v_t + (v^m)_{xx} + cv^p - dv^q = 0, m > 1, p > 0, c > 0, q > 0, d > 0, \\ v(x, 0) = v_0(x) \geq 0 \text{ with compact support,} \end{aligned} \quad (1.1)$$

governs the transport of turbulent kinetic energy k in the framework of a turbulence model with a single equation. This minimal model retains the essential physical ingredients: time evolution (∂_t), space diffusion (∂_x^2), one space dimension only, nonlinearity ($m \neq 1$), dissipation (cv^p) and production (dv^q). Our goal in the present paper is to find closed form solutions to serve as a validation test for the numerical schemes. In order to achieve that, we will not design new methods but apply existing methods to generate several new solutions of physical interest.

The so-called “model equation” [10] corresponds to $m = p = 3/2$, $c = d = 1$, $q = 1/2$, and the very special case $c = d = 0$ (of no interest to us) is known as the porous media equation [2,12].

In order to search for closed form solutions, it is better to first convert (1.1) to an algebraic equation,

$$v^{m-1} = w, w_t - mww_{xx} - \frac{m}{m-1}w_x^2 + (m-1)cv^{p-m-1} - (m-1)dw^{q-m-1} = 0, \quad (1.2)$$

with the choice $p = m$, $q = 2 - m$, m arbitrary (since it contains the case of physical interest $p = 3/2$, $q = 1/2$ when $m = 3/2$).

Therefore the final algebraic equation which we will study is (after rescaling t) [10, Eq. (3.24)]

$$\lambda v^{m-1} = w: E(w) \equiv w_t - bww_{xx} - w_x^2 + cw^2 - d = 0, b > 0, c > 0, d > 0. \quad (1.3)$$

Since there could exist physical systems not requiring the positivity of b , c , d , we will also mention a few solutions with b , c , d not all positive.

The paper is organized as follows. In Section 2 we first recall the ingenious, however not generalizable, method which has allowed Maire to obtain a solution matching all the physical constraints in (1.3).

Section 3 is devoted, using the method of infinitesimal Lie point symmetries, to the construction of all the reductions of the PDE (1.3) to an Ordinary Differential Equation (ODE), then to their integration.

In Section 4, we study the local behaviour of the field $w(x, t)$ near its movable singularities, a prerequisite to the search for closed form solutions.

The next Section 5 is devoted to a search for new exact solutions based on the singularity structure.

2. METHOD OF GALAKTIONOV AND POSASHKOV

The PDE (1.3) belongs to the class

$$w_t - P(\partial_x, w) = 0, P \text{ differential polynomial}, \tag{2.1}$$

with the additional property of existence of a finite number of functions $f_k(x)$ whose linear combinations are stable under $P(\partial_x, w)$,

$$\forall(\alpha_1, \dots, \alpha_K) \exists(\beta_1, \dots, \beta_K) : P\left(\partial_x, \sum_{k=1}^K \alpha_k f_k(x)\right) = \sum_{k=1}^K \beta_k f_k(x). \tag{2.2}$$

Then Galaktionov and Posashkov [7] observed that the (kind of “adiabatic”) assumption

$$w(x, t) = \sum_{k=1}^K \gamma_k(t) f_k(x), \tag{2.3}$$

amounts to solving a nonlinear system of ODEs (no more PDEs) for the functions $\gamma_k(t)$. In the present case (1.3),

$$w(x, t) = \gamma_1(t) + \gamma_2(t) \cosh(kx),$$

one thus obtains four solutions leaving the physical parameters b, c, d unconstrained and positive.

The most physically relevant solution [10, Eq. (3.37)],

$$\begin{cases} \lambda v^{m-1} = w = A \frac{\cosh(\omega t) - \cosh(kx)}{\sinh(\omega t)}, \\ \omega = Ac \frac{2+b}{1+b}, k^2 = \frac{c}{1+b}, A^2 = \frac{d}{c}, \end{cases} \tag{2.4}$$

does not depend on any movable (i.e. function of the initial conditions) constant, excluding of course the arbitrary origins x_0 and t_0 , and it provides a good description [10] of the transport of the turbulent kinetic energy.

The second solution is stationary,

$$w = A \cosh(kx), k^2 = \frac{c}{1+b}, A^2 = \frac{(1+b)d}{c}, \tag{2.5}$$

and the third one homogeneous in space

$$w = \frac{\omega_2}{2c} \tanh \frac{\omega_2}{2} t, \omega_2^2 = 4cd. \tag{2.6}$$

Finally, the fourth solution is characterized by a second order nonlinear ODE,

$$\begin{cases} w = g_0(t) + g_1(t) \cosh(kx), k^2 = \frac{c}{1+b}, g_1^2 = g_0^2 - \frac{d}{c} \neq 0, \\ -(b+1)g_0'' - 2(2b+3)cg_0'g_0' - 2(b+2)cg_0'(cg_0^2 - d) = 0, \end{cases} \tag{2.7}$$

and, if one excludes the particular values g_0 listed in the three previous solutions, its only physical (b positive) solutions are multivalued [3, Eq. (9.2)], but nevertheless expressible via quadratures [9]. The same kind of ODE will again be encountered hereafter, see Eq. (5.17) for F_1 .

If one relaxes the constraint $b > 0$, there also exists a fifth solution,

$$w = \frac{\omega_2}{2c} \tanh \frac{\omega_2}{2} t + A \cos(kx), \omega_2^2 = 4cd + 4c^2 A^2, k^2 = c, b = -2, A = \text{arbitrary.} \tag{2.8}$$

Since the above ingenious method only applies to the restricted class (2.1) and (2.2), let us in addition apply the two main classes of methods able to find explicit solutions of algebraic PDEs:

- Those based on the symmetries of the PDE, which generate reductions to ODEs;
- Those based on the movable singularities of the PDE, which (after a double study, local then global) generate closed form solutions $w(x, t)$.

3. SOLUTIONS OBTAINED BY SYMMETRIES

For generic values of b, c, d , the only Lie point symmetries of the PDE (1.3) are arbitrary translations of both x and t . The resulting characteristic system,

$$\frac{dx}{\alpha} = \frac{dt}{\beta} = \frac{dw}{0}, \alpha, \beta \text{ arbitrary constants,} \tag{3.1}$$

admits the two invariants w and $\beta x - \alpha t$, with α, β not both zero, thus defining the unique reduction to an ODE,

$$w(x, t) = W(\xi), \xi = \beta x - \alpha t, -\alpha W' - \beta^2 (bWW'' + W'^2) + cW^2 - d = 0. \tag{3.2}$$

One must distinguish $\beta \neq 0$ (the reduction preserves the differential order two) and $\beta = 0$ (the reduction lowers it to one).

For $\beta \neq 0$, since the positive parameter b is never equal to $-(1 - 1/n)$, with n some signed integer, the general solution $W(\xi)$ is multivalued [11] and generically cannot be obtained in closed form. A notable exception is $\beta \neq 0$ and $\alpha = 0$ (stationary wave),

$$\xi = x, w(x, t) = W(x), -bWW'' - W'^2 + cW^2 - d = 0, \tag{3.3}$$

which admits the first integral [10]

$$K = \left[(1 + b)(W'^2 - d) + cW^2 \right] W^{\frac{2}{b}}. \tag{3.4}$$

For $K = 0$, the general solution is physically acceptable and has already been obtained, see Eq. (2.5), and for $K \neq 0$ the solution is given implicitly by the quadrature

$$w(x, t) = W(x), x = x_0 + \int \left(\frac{1 + b}{(1 + b)d - cW^2 - KW^{\frac{-2}{b}}} \right)^{\frac{1}{2}} dW. \tag{3.5}$$

The only cases of invertibility of this quadrature are $-2/b = 1, 2, 3, 4$, yielding expressions $W(x)$ trigonometric ($b = -2, -1$) or elliptic ($b = -2/3, -1/2$), which however all violate the physical requirement $b > 0$.

For $\beta = 0$ one obtains the front independent of x , Eq. (2.6).

4. STRUCTURE OF SINGULARITIES

Any closed form solution depends on arbitrary functions or constants, such as x_0, t_0 in (2.4), which may define movable singularities. For instance, the solution (2.4) defines two families of movable singularities: on one side the movable poles of w located at the points $t = t_0 + n\pi/\omega, n \in \mathbb{Z}$, on the other side movable poles of $1/w$ (movable zeroes of w) located on the singular manifold $\varphi(x, t) = 0$ defined by

$$\varphi(x, t) \equiv \cosh \omega(t - t_0) - \cosh k(x - x_0) = 0. \tag{4.1}$$

A prerequisite to the systematic search for solutions is therefore the determination of the structure of the movable singularities of (1.3),

$$w \sim_{\varphi \rightarrow 0} w_0 \varphi^p, p \notin \mathcal{N}. \tag{4.2}$$

Since the highest derivative term $w w_{xx}$ displays the singularity $w = 0$, one must also study the movable zeros of w (movable poles of $w^{-1} = f$),

$$\lambda w^{m-1} = w = f^{-1} : E(f) \equiv -f^2 f_t + b f f_{xx} - (2b + 1) f_x^2 - d f^4 + c f^2 = 0. \tag{4.3}$$

This is a classical computation [6, §4.4.1], whose results are the following.

The PDE (1.3) admits two types of movable singularities.

- (1) If $\varphi_x = 0$ (the singular manifold is then said characteristic), the highest derivative term $w w_{xx}$ does not contribute to the leading order, and w (as well as f) presents one family of movable simple poles,

$$\varphi_x = 0 : w \sim_{\varphi \rightarrow 0} c^{-1} \varphi_t \varphi^{-1}, \tag{4.4}$$

$$\varphi_x = 0 : w^{-1} \sim_{\varphi \rightarrow 0} d^{-1} \varphi_t \varphi^{-1}. \tag{4.5}$$

- (2) If $\varphi_x \neq 0$ (noncharacteristic singular manifold), w has no movable poles and $w^{-1} = f$ presents two families of movable simple poles,

$$f \sim_{\varphi \rightarrow 0} f_0 \varphi_x \varphi^{-1}, \quad d f_0^2 - \frac{\varphi_t}{\varphi_x} f_0 + 1 = 0, \quad f_0 \neq 0. \tag{4.6}$$

To finish this local analysis, one must then compute the Fuchs indices of the linearized equation of (1.3) in the neighborhood of $\varphi = 0$. Indeed, a necessary condition of singlevaluedness is that all Fuchs indices be integers of any sign. For the families (4.4) or (4.5), the unique Fuchs index is $i = -1$. For each of the two families (4.6), one finds

$$i = -1, \quad \frac{d f_0^2 - 1}{b}, \tag{4.7}$$

and the noninteger value (even nonrational) of the second index reflects the high level of nonintegrability of the initial PDE.

In order to build solutions of this kind of nonintegrable PDE, the various methods based on the singularity structure are reviewed in summer school lecture notes [5], where the proper original references can be found. Let us now investigate a few of them.

5. TRUNCATIONS

They consist in requiring the Laurent series of a single family to terminate. For the respective local behaviours (4.4)–(4.6), the corresponding possible solutions are defined by

$$(\varphi_x = 0) : w = c^{-1} \chi^{-1} + w_1, \tag{5.1}$$

$$(\varphi_x = 0) : f = d^{-1} \chi^{-1} + f_1, \tag{5.2}$$

$$(\varphi_x \neq 0) : f = f_0 \chi^{-1} + f_1, \quad f_0 \neq 0, \tag{5.3}$$

in which the expansion variable $\chi(x, t)$ is any homographic transform of $\varphi(x, t)$ vanishing with φ . There exists an optimal choice of χ [4], characterized by its gradient ((ξ, η) represents either (x, t) or (t, x))

$$\chi_\xi = 1 + \frac{S}{2} \chi^2, \quad \chi_\eta = -C + C_\xi \chi - \frac{1}{2} (CS + C_{\xi\xi}) \chi^2, \tag{5.4}$$

and the constraint

$$S_\eta + C_{\xi\xi\xi} + 2C_\xi S + CS_\xi = 0. \tag{5.5}$$

After substitution in Eqs. (1.3) and (4.3), the LHS E of these equations become Laurent series in χ which also terminate,

$$E \equiv \sum_{j=0}^{-q} E_j \chi^{j+q}, \quad -q \in \mathbb{N}, \tag{5.6}$$

and the coefficients E_j only depend on w_0, w_1 (or f_0, f_1) and (S, C) . The solutions are then provided by solving the determining equations

$$\forall j = 0, \dots, -q : E_j(w_0, w_1, S, C) = 0. \tag{5.7}$$

5.1. Characteristic One-family Truncation of w

The truncation (5.1) with $\chi_x = 0$ defines the system

$$\begin{cases} E_0 \equiv 0, \\ E_1 \equiv -bc^{-1}w_{1,xx} + 2w_1 = 0, \\ E_2 \equiv -bw_1w_{1,xx} - w_{1,x}^2 + w_{1,t} + cw_1^2 - \frac{S}{2c} - d = 0, \end{cases} \tag{5.8}$$

whose general solution is

$$w_1 = A \cos(kx), S = -2cd - 2c^2A^2, k^2 = c, (b + 2)A = 0. \tag{5.9}$$

The value of χ results by integrating the Riccati system (5.4),

$$\chi^{-1} = \frac{\omega_2}{2} \tanh \frac{\omega_2}{2} t, \omega_2^2 = 4cd + 4c^2A^2. \tag{5.10}$$

The bifurcation $(b + 2)A = 0$ defines two previously found solutions w , (2.6) and (2.8).

5.2. Characteristic One-family Truncation of f

The truncation (5.2) with $\chi_t = 0$ defines the system

$$\begin{cases} E_0 \equiv 0, \\ E_1 \equiv f_1 = 0, \\ E_2 \equiv cd + \frac{S}{2} - 5d^2f_1^2 - df_{1,t} = 0, \\ E_3 \equiv 2cdf_1 + Sf_1 - 4d^2f_1^3 - 2df_1f_{1,t} + bdf_{1,xx} = 0, \\ E_4 \equiv E(f_1) + \frac{S}{2d}f_1^2 = 0, \end{cases} \tag{5.11}$$

whose general solution is

$$f_1 = 0, S = -2cd. \tag{5.12}$$

After integration of the Riccati system (5.4),

$$\chi^{-1} = \frac{\omega_2}{2} \tanh \frac{\omega_2}{2} t, \omega_2^2 = 4cd, \tag{5.13}$$

one obtains

$$f = d^{-1} \frac{\omega_2}{2} \tanh \frac{\omega_2}{2} t, \omega_2^2 = 4cd, \tag{5.14}$$

identical to (2.6).

To conclude, these characteristic truncations yield nothing new.

5.3. Noncharacteristic One-family Truncation of f

Let us finally consider one of the two families (4.6), whose Fuchs indices are (4.7), and let us assume $bd \neq 0$. The truncation (5.3) defines the system

$$\begin{cases} E_0 \equiv df_0^2 + Cf_0 + 1 = 0, \\ E_1 \equiv 2(-2df_0^2 - Cf_0 + b)f_1 + f_0^2 C_x - f_0 f_{0,t} + 2(1+b)f_{0,x} = 0, \\ E_j \equiv E_j(f_0, f_1, S, C) = 0, j = 2, 3, \\ E_4 \equiv b(2b+1) \left[f_0^2 S + 2f_1^2 + 2f_1 f_{0,x} - 2f_0 f_{1,x} \right]^2 = 0, \\ X \equiv S_t + C_{xxx} + 2C_x S + CS_x = 0, \end{cases} \tag{5.15}$$

and the factorization of E_4 makes the resolution easy. It is even easier after the change of functions

$$(f_0, f_1) \rightarrow (F_0, F_1): f_0 = 1/F_0, f_1 = f_0 F_1 - \frac{1}{2} f_{0,x}. \tag{5.16}$$

In the case $b \neq -1/2$, the algebraic (i.e. nondifferential) elimination of $F_{0,t}, F_{1,t}, S_x$ yields the much simpler equivalent system,

$$b \neq -\frac{1}{2}: \begin{cases} E_1 \equiv F_{0,t} - (b+2)F_0 F_{0,x} + 2(b+1)F_0^2 F_1 - 2dF_1 = 0, \\ E_2 \equiv -bF_{0,xx} + 2(b+2)F_1 F_{0,x} + 2[(3b+2)F_{1,x} - (4(b+1)F_1^2 + c)]F_0 - 2F_{1,t} = 0, \\ X \equiv bF_{1,xx} - 2(3b+2)F_1 F_{1,x} + 4(b+1)F_1^3 - cF_1 = 0, \\ S = \frac{F_{0,xx}}{F_0} - \frac{3}{2} \frac{F_{0,x}^2}{F_0^2} - 2F_1^2 + 2F_{1,x} - 2 \frac{F_{0,x}}{F_0} F_1, \\ C = -F_0 - dF_0^{-1}. \end{cases} \tag{5.17}$$

This system (5.17) is solved in three steps:

- (i) integration of the ODE in F_1 defined by $X = 0$, which introduces at most two arbitrary functions of t ;
- (ii) determination of F_0 by solving the overdetermined system ($E_1 = 0, E_2 = 0$);
- (iii) knowing the values of (S, C) , integration of the Riccati system (5.4) for χ .

In the unphysical case $b = -1/2$, we could not find an equivalent system as simple as (5.17).

Let us now perform the above mentioned three steps.

5.3.1. Values of F_1

As already mentioned about the similar ODE (2.7), we will discard the multivalued solutions of the ODE $X = 0$ for $F_1(t)$, referring the interested reader to Ref. [9].

All singlevalued solutions of the ODE for F_1 are obtained by two methods: for the general solution, by looking in the classical exhaustive tables [8,11]; for particular solutions, by looking for Darboux polynomials. One thus finds exactly seven solutions, five of them with a negative b (unphysical for the diffusion problem, but possibly admissible for other systems) and two with an arbitrary value of b ,

$$b = -\frac{4}{3}: F_1 = -\partial_x \log \left[\cosh(kx - g(t)) - \cosh(K(t)) \right], k^2 = -\frac{3}{4}c, \tag{5.18}$$

$$b = -\frac{4}{5}: F_1 = -\partial_x \log \left[\wp(x - g(t)) - e_0 \right], e_0 = -\frac{5c}{48}, g_2 = 12e_0^2, g_3(t), \tag{5.19}$$

$$b = -\frac{1}{2}: F_1 = \frac{1}{2} \partial_x \log \left[\wp(x - g(t)) - e_0 \right], e_0 = \frac{c}{6}, g_2 = 12e_0^2, g_3(t), \tag{5.20}$$

$$b = -\frac{2}{3}: F_1 = \sqrt{\wp(x - g(t)) - e_0}, e_0 = -\frac{c}{2}, g_2 = 12e_0^2 - 4K(t), g_3 = -8e_0^3 + 4e_0 K(t), \tag{5.21}$$

$$b + 1 \neq 0: F_1 = -\frac{k}{2} \tanh \frac{k}{2} (x - g(t)), k^2 = \frac{c}{b+1}, \tag{5.22}$$

$$b + 1 \neq 0: F_1 = -\frac{b}{2(b+1)} \frac{k}{2} \tanh \frac{k}{2} (x - g(t)), k^2 = \frac{4(b+1)c}{b^2}, \tag{5.23}$$

$$b = -2: F_1 = 0, \tag{5.24}$$

in which $\wp(x, g_2, g_3)$ is the elliptic function of Weierstrass, and g, K two arbitrary functions of t . The first four depend on two arbitrary functions of t , the next two on one arbitrary function of t .

For $b = -1/2$, the obtained solution is a particular case of the solution, which we could not obtain, resulting from the system (5.15).

For $b = -1$ and $c \neq 0$, the ODE for F_1 has no singlevalued solution.

Let us next determine F_0 . By the elimination of F_1 between $E_1 = 0$ and $E_2 = 0$, the value of F_0 is the root of a sixth degree polynomial whose coefficients are polynomial in F_1 and its derivatives. However, this computation is only tractable for the two tanh solutions (which only depend on $g(t)$), and one finds constant values for F_0 and $g'(t)$,

$$b + 1 \neq 0: F_0^2 = \frac{d}{b + 1}, g'(t) = + (b + 2) \frac{k}{2} F_0, \tag{5.25}$$

$$b + 1 \neq 0: F_0^2 = \frac{d}{b + 1}, g'(t) = - (b + 2) \frac{k}{2} F_0. \tag{5.26}$$

In the four other cases $b = -4/3, -4/5, -1/2, -2/3$ of the list (5.18)–(5.21), this technical difficulty is overcome by integrating the linear inhomogeneous ODE $E_2 = 0$ for F_0 as follows.

One first notices that, in its homogeneous part, the simple pole of F_1 with residue $r = -1$ is a Fuchsian singularity for the EDO in F_0 , whose Fuchs indices i , the roots of

$$bi^2 - (b + 4r + 2br)i + 8(b + 1)r^2 + 2(3b + 2)r = 0, \tag{5.27}$$

are irrational for the four values of b . Since F_0 is necessarily an algebraic function of F_1 and its derivatives, the only such algebraic solution of the homogeneous part of $E_2 = 0$ is $F_0 = 0$, see the example Eq. (5.34) hereafter. One then computes F_0 as a particular solution of the inhomogeneous equation $E_2 = 0$. Once this value of F_0 obtained, the nonlinear equation $E_1 = 0$ generates constraints on $g(t)$ and $K(t)$. This method is exemplified in Subsection 5.3.5.

5.3.2. Solution, case of the first tanh value of F_1

Given

$$b + 1 \neq 0: F_0 = \frac{1}{a_0}, a_0^2 = \frac{b + 1}{d}, g'(t) = + (b + 2) \frac{k}{2} F_0, \tag{5.28}$$

one finds successively

$$S = -\frac{k^2}{2}, C = -\frac{b + 2}{a_0}, \tag{5.29}$$

then, by integration of the Riccati system (5.4)

$$\chi^{-1} = \frac{k}{2} \tanh \frac{k}{2} \left(x + \frac{b + 2}{a_0} t \right), \tag{5.30}$$

the solution

$$w^{-1} = f = a_0 \frac{k}{2} \left[\tanh \frac{k}{2} \left(x + \frac{b + 2}{a_0} t \right) - \tanh \frac{k}{2} \left(x - \frac{b + 2}{a_0} t \right) \right], k^2 = \frac{c}{b + 1}, \tag{5.31}$$

which is just another representation of the solution (2.4) already found by the method of Galaktionov and Posashkov.

5.3.3. Solution, case of the second tanh value of F_1

Solving (E_1, E_2) for $(F_0(x, t), g(t))$ is again quite easy,

$$F_0(x, t) = \text{const} = \frac{1}{a_0}, a_0^2 = \frac{b + 1}{d}, g(t) = -\frac{(b + 2)k}{2a_0} t,$$

then one obtains

$$S = -\frac{b}{b+1} \frac{k^2}{4} + \frac{b(b+2)}{2(b+1)^2} \frac{k^2}{4} \tanh^2 \frac{k}{2} \left(x + \frac{b+2}{a_0} t \right), C = -\frac{b+2}{a_0}.$$

The ODE for χ^{-1} is a Lamé equation in its Riccati form, whose solution is singlevalued for $b = -1 + 1/n, n \in \mathbb{Z}$, multivalued otherwise. For the present diffusion problem, this new solution leaves b, c, d unconstrained and can indeed be used to test the validity of numerical schemes.

5.3.4. Case $b = -2$

A computation similar to the above one yields

$$F_1 = 0, F_0 = A \cosh kx, S = -c \left[1 - \frac{3}{2} \tanh^2 kx \right], C = -\frac{A^2 + d}{d} \cosh kx, k^2 = -c, \tag{5.32}$$

then

$$\chi^{-1} = \partial_x \log \left[\cosh(kx)^{-1/2} \left(-\frac{\Omega}{Ak} \cosh(\Omega t) + \sinh(\Omega t) \cosh(kx) \right) \right], \Omega^2 = (A^2 + d)c, \tag{5.33}$$

i.e. a solution identical to (2.8) already found in Section 2.

5.3.5. Solutions, case $b = -4/3$

The resolution of the four cases $b = -4/3, -4/5, -1/2, -2/3$ follows the same pattern, so we only detail it for $b = -4/3$ [Eq. (5.18)].

For this value $b = -4/3$, the ODE $E_2 = 0$ possesses the general solution

$$\begin{aligned} F_0 = & g_+(t) \frac{[\cosh K(t) \cosh(kx - g(t)) + \sinh K(t) \sinh(kx - g(t)) - 1]^{\sqrt{2}}}{(\cosh(kx - g(t)) - \cosh K(t))^{\sqrt{2}-1}} \\ & + g_-(t) \frac{[\cosh K(t) \cosh(kx - g(t)) + \sinh K(t) \sinh(kx - g(t)) - 1]^{-\sqrt{2}}}{(\cosh(kx - g(t)) - \cosh K(t))^{-\sqrt{2}-1}} \\ & + 3 \frac{[K' \sinh K(t) \sinh(kx - g(t)) + g' \cosh K(t) \cosh(kx - g(t)) - g'_-]}{2k \sinh^2 K(t)}, \end{aligned} \tag{5.34}$$

in which $g_{\pm}(t)$ are two other arbitrary functions of t .

As already argued in Subsection 5.3.1, since the relation between F_0 and $e^{kx-g(t)}$ is necessarily algebraic, the two functions g_+ and g_- must vanish. Equation $E_1 = 0$ then yields the necessary and sufficient conditions,

$$g'' = 0, K'' = 0, g'K' = 0, g'^2 + K'^2 = cd, \tag{5.35}$$

solved as

$$g(t) = \omega_1 t, K(t) = \Omega_1 t + k_0, \omega_1 \Omega_1 = 0, \omega_1^2 + \Omega_1^2 = cd, \tag{5.36}$$

in which ω_1, Ω_1, k_0 are constant.

The system (5.17) therefore has for solution, in the first case $\omega_1 \neq 0, \Omega_1 = 0$,

$$\begin{cases} F_1 = -\partial_x \log[\cosh(kx - \omega_1 t) - \cosh k_0], k^2 = -\frac{3}{4}c, \omega_1^2 = cd, \\ F_0 = \frac{3\omega_1}{2k \sinh^2 k_0} [\cosh k_0 \cosh(kx - \omega_1 t) - 1], \\ S = -\frac{k^2}{2} \left[1 - \frac{3 \sinh^2 k_0}{(\cosh k_0 \cosh(kx - \omega_1 t) - 1)^2} \right], \\ C = -\frac{\omega_1}{2k} \frac{3(\cosh k_0 \cosh(kx - \omega_1 t) - 1)^2 - \sinh^4 k_0}{\sinh^2 k_0 (\cosh k_0 \cosh(kx - \omega_1 t) - 1)}, \end{cases} \tag{5.37}$$

and in the second case $\omega_1 = 0, \Omega_1 \neq 0$,

$$\begin{cases} F_1 = -\partial_x \log[\cosh kx - \cosh \Omega_1 t], F_0 = \frac{3\Omega_1 \sinh kx}{2k \sinh \Omega_1 t}, k^2 = -\frac{3}{4}c, \Omega_1^2 = cd, \\ S = -\frac{k^2}{2} \left(1 + \frac{3}{\sinh^2 kx}\right), C = \frac{\Omega_1}{2k} \left[\frac{\sinh \Omega_1 t}{\sinh kx} - 3 \frac{\sinh kx}{\sinh \Omega_1 t}\right]. \end{cases} \tag{5.38}$$

The integration of the Riccati system (5.4)–(5.4) introduces another arbitrary constant t_0 , then the solutions w are defined by (5.3) and (5.16). One thus obtains two solutions w , respectively

$$\begin{cases} \mathcal{X}^{-1} = \frac{k a_1 \sinh \xi (\cosh k_0 \sinh \xi + \cosh^2 k_0 - 2) + a_2 (\cosh k_0 \sinh^2 \xi - 2 \sinh \xi + \cosh k_0)}{2 [a_1 (\sinh \xi - \cosh k_0) + a_2 \sinh \xi] [\cosh k_0 \sinh \xi - 1]}, \\ \frac{a_1}{a_2} = \frac{\omega_4 \tanh(\omega_4 (t - t_0))}{2\omega_1}, \xi = kx - \omega_1 t, k^2 = -\frac{3}{4}c, \omega_1^2 = cd, \omega_4^2 = \left(1 - \frac{3}{\sinh^2 k_0}\right)cd, \\ w = \frac{3\omega_1 (\cosh k_0 - \cosh \xi)}{2k \sinh^2 k_0} \left[\omega_1 - \frac{\omega_4}{2} \tanh(\omega_4 (t - t_0)) (\cosh k_0 - \cosh \xi)\right], \end{cases} \tag{5.39}$$

and

$$\begin{cases} \mathcal{X}^{-1} = \frac{k a_1 (\cosh^2 kx - 2) - a_2 \cosh kx}{2 [a_1 \cosh kx + a_2] \sinh kx}, k^2 = -\frac{3}{4}c, \\ \frac{a_1}{a_2} = \frac{3 \sinh(2\Omega_1 t) - 6\Omega_1 (t - t_0)}{6 \sinh \Omega_1 t - 2 \sinh^3(\Omega_1 t) - 6\Omega_1 (t - t_0) \cosh \Omega_1 t}, \Omega_1^2 = cd, \\ w = \frac{3\Omega_1 [\cosh \Omega_1 t - \cosh kx] [a_1 \cosh kx + a_2]}{2k^2 \sinh \Omega_1 t [a_1 \cosh \Omega_1 t + a_2]}. \end{cases} \tag{5.40}$$

Each of these two new solutions is outside the class (2.4) and depends on a single arbitrary constant (k_0 in the first one, t_0 in the second one).

5.3.6. Case $b = -4/5$

With the value (5.19) of F_1 , the function F_0 , algebraic in the derivatives of F_1 , is necessarily an affine function of ζ, \wp' and $x - g$ [1, §18.6],

$$F_0 = R_0 + R_1 \wp' + R_2 \zeta + (x - g(t))R_3, \tag{5.41}$$

whose coefficients R_i are rational in $\wp(x - g(t))$. One then proves that, since d is nonzero, the discriminant $g_2^3 - 27g_3^2$ must vanish, thus reducing F_1 and F_0 to simply periodic functions,

$$\begin{cases} F_1 = -\partial_x \log \psi(x, t), \psi = (k \tanh(k(x - g(t))))^2 - (2/3)k^2 - e_0, k^2 = 3\epsilon e_0, \epsilon^2 = 1, \\ F_0 = -\frac{5}{6}g' [1 + (l_3 - 1/8)e_0^3 \psi^3], (\epsilon - 1)l_3 = 0. \end{cases} \tag{5.42}$$

Equation $E_1 = 0$ then generates the constraints

$$\epsilon = 1, g'^2 = \frac{36}{5}d, \tag{5.43}$$

thus restricting this solution to the particular case $b = -4/5$ of (5.23).

5.3.7. Case $b = -1/2$

Since we could not solve the system (5.15), we only solve here its particular case (5.17). One first establishes the particular solution F_0 of $E_2 = 0$, namely, in the elliptic subcase $g_2^3 - 27g_3^2 \neq 0$,

$$y = \wp(x - g(t)) - e_0, F_0 = \frac{2y^3 + g_3 + 8e_0^3}{y^3} \left[\frac{g'}{3} - \frac{3g_3'}{2\Delta} ((x - g)g_3 - 8e_0^2 \zeta) \right] - \frac{3g_3'}{2\Delta} (8e_0^2 y^2 - (g_3 + 8e_0^3)(y - 2e_0)) \wp', \Delta = 27(64e_0^6 - g_3^2), \quad (5.44)$$

and in the trigonometric subcase $g_2^3 - 27g_3^2 = 0$,

$$F_1 = \frac{1}{2} \partial_x \log \psi(x, t), \psi = (k \tanh(k(x - g(t))))^2 - (2/3)k^2 - e_0, k^2 = \pm 3e_0, \quad (5.45)$$

$$F_0 = \frac{2}{3} g' \left[1 + \frac{4(1 - \varepsilon)e_0^3}{\psi^3} \right].$$

Equation $E_1 = 0$ then generates the constraints $g' = 0$ in the elliptic subcase, and $\varepsilon = -1, g'^2 = 9d/2$ in the trigonometric subcase, restricting the solution to (5.23) with $b = -1/2$.

5.3.8. Case $b = -2/3$

This case also happens to be a particular case of (5.23).

6. CONCLUSION

By a systematic investigation, we have obtained several new solutions of this diffusion problem. Two of them [Subsection 5.3.3, Eq. (2.7)] match all the physical constraints $b > 0, c > 0, d > 0$ and can serve to calibrate and validate the numerical schemes.

The two other new solutions, Eqs. (5.39) and (5.40), only valid for a negative value of b , could be useful for other diffusion problems governed by (1.3) with $b < 0$.

Finally, in this short paper we have only investigated those solutions w which take into account one of the two movable poles. Taking account of both poles *via* the two-singular manifold method (see [6, §3.2.4.2] and references therein) should certainly generate additional solutions.

Remark. As suggested by the two new solutions Eqs. (5.39) and (5.40), the class w equal to a second degree polynomial in $\cosh(kx)$ with time-dependent coefficients could also generate physically interesting solutions.

CONFLICTS OF INTEREST

The author declares no conflicts of interest.

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REFERENCES

- [1] M. Abramowitz, I.A. Stegun, Handbook of Mathematical Functions, tenth printing, Dover, New York, 1972.
- [2] D.G. Aronson, Regularity properties of flows through porous media, SIAM J. Appl. Math. 17 (1969), 461–467.
- [3] F.J. Bureau, Differential equations with fixed critical points, Annali Mat. Pura Appl. 64 (1964), 229–364.
- [4] R. Conte, Invariant painlevé analysis of partial differential equations, Phys. Lett. A 140 (1989), 383–390.
- [5] R. Conte, Exact solutions of nonlinear partial differential equations by singularity analysis, in: A. Greco (ed.), Direct and inverse methods in nonlinear evolution equations, Lecture Notes in Physics, vol. 632, Springer Verlag, Berlin, 2003, pp. 1–83.
- [6] R. Conte, M. Musette, The Painlevé Handbook, second edition, Springer, Switzerland, 2020.
- [7] V.A. Galaktionov, S.A. Posashkov, Exact solutions and invariant spaces for nonlinear gradient diffusion equations, Comput. Math. Math. Phys. 34 (1994), 313–321.
- [8] B. Gambier, Sur les équations différentielles du second ordre et du premier degré dont l'intégrale générale est a points critiques fixes, Acta Math. 33 (1910), 1–55.
- [9] R.L. Lemmer, P.G.L. Leach, The Painlevé test, hidden symmetries and the equation $y'' + yy' + ky^3 = 0$, J. Phys. A 26 (1993), 5017–5024.

- [10] P.H. Maire, Étude d'une équation de diffusion non-linéaire. Application à la discrétisation de l'équation d'énergie cinétique turbulente pour un modèle de turbulence à une équation, 2001, p. 81, available from: <https://hal-cea.archives-ouvertes.fr/cea-02931269/document> Rapport CEA D01 03661.
- [11] P. Painlevé, Mémoire sur les équations différentielles dont l'intégrale générale est uniforme, *Bull. Soc. Math. France* 28 (1900), 201–261.
- [12] Y.B. Zel'dovich, Y.P. Raizer, Preface to the English edition, *Physics of shock waves and high-temperature hydrodynamic phenomena*, vol. 2, Academic Press, New York, 1967.