On Solutions of Generalized Kinetic Equations of Fractional Order

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ABSTRACT: The object of the present paper is to derive the solution of generalized kinetic equations of fractional order involving the Wright generalized Bessel function or Bessel-Mitland function. Results obtained by Chaurasia and Pandey [24] are derived more precisely through results obtained in the present paper in terms of $K_4$ - function obtained by Sharma [12] believed to be new. Special case, involving the $F$-function is considered.

Key Words: Fractional kinetic equations, Fractional Calculus, $K_4$ - function, Laplace transform and Bessel-Mitland function.

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1. Introduction

Fractional Calculus and special functions have contributed a lot to mathematical physics and its various branches. The great use of mathematical physics in distinguished astrophysical problems has attracted astronomers and physicists to pay more attention to available mathematical tools that can be widely used in solving several problems of astrophysics/physics. The fractional kinetic equations discussed here can be used to investigate a wide class of known fractional kinetic equations. A spherically symmetric non-rotating, self-gravitating model of star like the sun is assumed to be in thermal equilibrium and hydro static equilibrium. The star is characterized by its mass, luminosity effective surface temperature, radius, central density and central temperature. The stellar structures and their mathematical models are investigated on the basis of above characters and some additional information related to the equation of nuclear energy generation rate and the opacity.

Consider an arbitrary reaction characterized by a time dependent quantity $N = N(t)$. It is possible to calculate the rate of change by the equation $\frac{dN}{dt} = -d + p$. In general, through feedback or other interaction mechanism, destruction and production depend on the quantity $N$ itself: $d = d(N)$ or $p = p(N)$. This dependence is complicated since the destruction or production at time $t$ depend not only on $N(t)$.
but also on the past history $N(\tau), \tau < t$, of the variable $N$. This may be represented by Haubold and Mathai [10]

$$\frac{dN}{dt} = -d(N_i) + p(N_i)$$

(1.1)

where $N_i$ denotes the function defined by $N_i(t^*) = N(t - t^*), t^* > 0$.

Haubold and Mathai [10] studied a special case of this equation, when spatial fluctuation or inhomogenities in quantities $N(t)$ are neglected, is given by the equation

$$\frac{dN_i}{dt} = -c_i N_i(t)$$

(1.2)

with the initial condition $N_i(t = 0) = N_0$ is the number of density of species $i$ at time $t = 0$; constant $c_i > 0$, known as standard kinetic equation. A detailed discussion of the above equation is given in Kourganoff [25]. The solution of (1.2) is given by

$$N_i(t) = N_0 e^{-c_i t}$$

(1.3)

An alternative form of this equation can be obtained on integration:

$$N(t) - N_0 = c_0 D^{-1}_t N(t),$$

(1.4)

where $D^{-1}_t$ is the standard fractional integral operator. Haubold and Mathai [10] have given the fractional generalization of the standard kinetic equation (1.2) as

$$N(t) - N_0 = c_0^\nu D^{-\nu}_t N(t),$$

(1.5)

where $D^{-\nu}_t$ is the well known Riemann-Liouville fractional integral operator (Oldham and Spanier [11]; Samko, Kilbas and Marichev [20]; Miller and Ross [14]) defined by

$$D^{-\nu}_t f(x) = \frac{1}{\Gamma(\nu)} \int_0^t (t - u)^{\nu-1} f(u) du, R(\nu) > 0.$$ 

(1.6)

The solution of fractional kinetic equation (1.5) is given by (see Haubold and Mathai [10])

$$N(t) = N_0 \sum_{k=0}^{\infty} \frac{(-1)^k}{\Gamma(\nu k + 1)} (ct)^{\nu k}.$$ ...

(1.7)

Further Saxena and Mathai and Haubold [15] studied the generalizations of the fractional kinetic equation in terms of the Mittag-Leffler functions which extended the work of Haubold and Mathai [10]. In an another paper, Saxena and Mathai and Haubold [16] developed the solutions for fractional kinetic equations associated with the generalized Mittag-Leffler function and R-function.

The fractional kinetic equations are also studied by many authors viz. Hille and Tamarkin [6], Glockle and Nonnenmacher [26], Saichev and Zaslavsky [3], Saxena...
et al. [15,16,17], Zaslavsky [7], Saxena and Kalla [19], Chaurasia and Pandey [23,24], Chaurasia and kumar [22] etc. for their importance in the solution of certain physical problems. Recently, Saxena et al. [18] investigated the solution of fractional reaction equation and the fractional diffusion equation. Laplace transform technique is used.

In the present article we introduce and investigate the further computable extensions of the generalized fractional kinetic equation. The fractional kinetic equation and its solution, discussed in terms of the Wright generalized Bessel function, are written in compact and easily computable form.

The wright generalized Bessel function and its relationship with some other functions

\[
J_{\nu}^\delta(z) = \sum_{k=0}^{\infty} \frac{(-z)^k}{k!\Gamma(\delta k + \nu + 1)}, \tag{1.8}
\]

where \( z \in c, \delta > 0 \) and \( \nu > -1 \). The generalized Wright function yields the following relationships with various classical special functions:

**Wright function**

\[
J_{\nu-1}^\delta(z) = W(-z; \delta; \nu) = \sum_{k=0}^{\infty} \frac{(-z)^k}{k!\Gamma(\delta k + \nu)}.
\tag{1.9}
\]

**Mittag-Leffler function** \(\\text{(Mittag [8] and [9])}\)

\[
J_{0}^\delta(z) = \frac{1}{k!} E_{\delta}(-z) = \frac{1}{k!} \sum_{k=0}^{\infty} \frac{(-z)^k}{\Gamma(\delta k + 1)}.
\tag{1.10}
\]

**Generalized Mittag-Leffler function** \(\text{(Wiman [2])}\)

\[
J_{\nu-1}^\delta(z) = \frac{1}{k!} E_{\delta,\nu}(-z) = \frac{1}{k!} \sum_{k=0}^{\infty} \frac{(-z)^k}{\Gamma(\delta k + \nu)}.
\tag{1.11}
\]

**Miller and Ross function** \(\text{[14]}\)

\[
J_{\nu}^{1}(az) = \frac{1}{k!}z^{\nu} E_{\nu}(\nu, -a) = \frac{1}{k!} \sum_{k=0}^{\infty} \frac{(-az)^k}{\Gamma(k + \nu + 1)}.
\tag{1.12}
\]

2. Extensions of generalized fractional kinetic equations

**Theorem 2.1.** If \( \delta > 0, \mu + 1 > 0, \nu > 0 \) and \( c > 0 \), then for the solution of the equation

\[
N(t) - N_0 = -c^\nu D_t^{-\nu} N(t), \tag{2.1}
\]

there holds the formula

\[
N(t) = N_0 E_{\nu,k+1}(-t) E_{\nu,k+1}(c^\nu t^\nu). \tag{2.2}
\]
**Proof:** We know that (Erdélyi et al. [1]) the Laplace transform of the Riemann-Liouville fractional integral is given by

\[ L\{\alpha D_t^{-\sigma} f(t); p\} = p^{-\sigma} F(p), \tag{2.3} \]

where

\[ F(p) = \int_{u=0}^{\infty} e^{-pu} f(u) du. \tag{2.4} \]

Now taking the Laplace transform of both sides of (2.1), we have

\[ L\{N(t); p\} - N_0 L\{J_\mu^\delta(t); p\} = -c^\nu L\{\alpha D_t^{-\nu} N(t); p\} \]

\[ N(p) - N_0 \int_0^\infty e^{-pt} \sum_{k=0}^\infty \frac{(-t)^k}{k! \Gamma(\delta k + \mu + 1)} dt = -c^\nu p^{-\nu} N(p), \]

\[ N(p)[1 + c^\nu p^{-\nu}] = N_0 \sum_{k=0}^\infty \frac{(-1)^k}{k! \Gamma(\delta k + \mu + 1)} \int_0^\infty e^{-pt} t^{k+1} dt \]

By virtue of the relationship, we have

\[ L^{-1}\{p^{-\rho}\} = \frac{t^{\rho-1}}{\Gamma\rho}, R(\rho) > 0. \tag{2.5} \]

\[ N(p)[1 + c^\nu p^{-\nu}] = N_0 \sum_{k=0}^\infty \frac{(-1)^k \Gamma k + 1}{\Gamma(\delta k + \mu + 1) p^{k+1}} \]

\[ N(p)[1 + c^\nu p^{-\nu}] = N_0 \sum_{k=0}^\infty \frac{(-1)^k}{\Gamma(\delta k + \mu + 1) p^{k+1}} \]

\[ N(p) = N_0 \sum_{k=0}^\infty \frac{(-1)^k}{\Gamma(\delta k + \mu + 1)} \sum_{r=0}^\infty \frac{(-1)^r}{(r)!} \frac{p^{-(k+1)}}{t^{\nu r}} \left(\sum_{r=0}^{\nu r + \nu + 1} \frac{(-1)^r}{(r)!}\right) \]

Taking inverse Laplace transform, we have

\[ L^{-1}\{N(p)\} = N_0 \sum_{k=0}^\infty \frac{(-1)^k}{\Gamma(\delta k + \mu + 1)} \left\{ L^{-1}\left\{ \frac{t^{\nu r}}{\Gamma(\nu r + k + 1)} \right\} \right\} \]

\[ N(t) = N_0 \sum_{k=0}^\infty \frac{(-1)^k t^k}{\Gamma(\delta k + \mu + 1)} \left\{ \sum_{r=0}^\infty \frac{(-1)^r}{(r)!} \frac{t^{\nu r}}{\Gamma(\nu r + k + 1)} \right\} \]

\[ N(t) = N_0 \sum_{k=0}^\infty \frac{(-1)^k t^k}{\Gamma(\delta k + \mu + 1)} \left\{ \sum_{r=0}^\infty \frac{(-1)^r}{(r)!} \frac{t^{\nu r}}{\Gamma(\nu r + k + 1)} \right\} \]
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\[ N(t) = N_0 E_{\delta,\mu+1}(-t)E_{\nu,k+1}(-e^{rt^\nu}). \]  

(2.6)

Then theorem is, thus, completely proved. \(\square\)

**Corollary 2.2.** If \(c > 0, b = 0, \delta > 0, \nu > 0, \mu > 0, \delta\nu - \mu > 0\), then for the solution of the equation

\[ N(t) - N_0 K_4^{(\nu,\mu,\delta),(-e^{-\nu},0):(p,q)}(t) = -\sum_{r=1}^{n} \left(\frac{n}{r}\right) e^{r\nu_0 D_1^{-r\nu}} N(t), \]  

(2.7)

there holds the formula

\[ N(t) = N_0 K_4^{(\nu,\mu+\nu n,\delta+n),(-e^{-\nu},0):(p,q)}(t), \]  

(2.8)

provided both sides of (2.8) exist.

**Proof:** The \(K_4\) - function \[12\] is defined as

\[ K_4^{(\alpha,\beta,\gamma),(a,c):(p,q)}(x) = K_4^{(\alpha,\beta,\gamma),(a,c):(p,q)}(x) = \sum_{n=0}^{\infty} \left(\frac{a_1 \cdots a_p}{b_1 \cdots b_q}\right) n! \Gamma((n+\gamma)\alpha - \beta) \]

where \(R(\alpha \gamma - \beta) > 0\) and \((a_i)_n\) \((i = 1, 2, \ldots, p)\) and \((b_j)_n\) \((j = 1, 2, \ldots, q)\) are the pochhammer symbols and none of the parameters \(b_j\)'s is a negative integer or zero. Taking Laplace transform of both sides of the equation (2.7), we have

\[ L\{N(t)\} = L\{N_0 K_4^{(\nu,\mu,\delta),(-e^{-\nu},0):(p,q)}(t)\} = L\{-\sum_{r=1}^{n} \left(\frac{n}{r}\right) e^{r\nu_0 D_1^{-r\nu}} N(t)\} \]

or

\[ N(p) = N_0 \frac{p^{\mu-\nu}}{1 + p^{e^{\nu}c^{\nu}}} \sum_{k=0}^{\infty} \left(\frac{a_1 \cdots a_p}{b_1 \cdots b_q}\right) k! \Gamma((k+\gamma)\alpha - \beta) \]  

(2.9)

Finally taking the inverse Laplace transform of equation (2.9), we have

\[ L^{-1}\{N(p)\} = L^{-1}\{N_0 \frac{p^{\mu-\nu}}{1 + p^{e^{\nu}c^{\nu}}} \sum_{k=0}^{\infty} \left(\frac{a_1 \cdots a_p}{b_1 \cdots b_q}\right) k! \} \]

or

\[ N(t) = N_0 K_4^{(\nu,\mu+\nu n,\delta+n),(-e^{-\nu},0):(p,q)}(t) \]  

\(\square\)
Corollary 2.3. If $c > 0$, $b \geq 0$, $\delta > 0$, $\nu > 0$, $\mu > 0$, $\delta \nu - \mu > 0$, then for the solution of the equation

$$N(t) - N_0 K_4^{(\nu, \delta \nu - \mu, \delta, (c^{-\nu}, b); (p, q)}(t) = - \sum_{r=1}^{n} \binom{n}{r} e^{\nu \tau} D_{\tau}^{\nu} N(t),$$

(2.10)

there holds the formula

$$N(t) = N_0 K_4^{(\nu, (\delta + \nu) \nu - \mu, (\delta + \nu), (c^{-\nu}, b); (p, q)}(t),$$

(2.11)

provided both sides of (2.11) exist.

Corollary 2.4. If $c > 0$, $b = 0$, $\delta > 0$, $\nu > 0$, $\mu > 0$, $\delta \nu - \mu > 0$, then for the solution of the equation

$$N(t) - N_0 K_4^{(\nu, \nu - \mu, \delta, (c^{-\nu}, 0); (p, q)}(t) = - \sum_{r=1}^{n} \binom{n}{r} e^{\nu \tau} D_{\tau}^{\nu} N(t),$$

(2.12)

there holds the formula

$$N(t) = N_0 K_4^{(\nu, (\delta + \nu) \nu - \mu, (\delta + \nu), (c^{-\nu}, 0); (p, q)}(t),$$

(2.13)

provided both sides of (2.13) exist.

Corollary 2.5. If $c > 0$, $b \geq 0$, $\delta > 0$, $\nu > 0$, $\mu > 0$, $\nu - \mu > 0$, then for the solution of the equation

$$N(t) - N_0 K_4^{(\nu, \mu, 1), (c^{-\nu}, b); (p, q)}(t) = - \sum_{r=1}^{n} \binom{n}{r} e^{\nu \tau} D_{\tau}^{\nu} N(t),$$

(2.14)

there holds the formula

$$N(t) = N_0 K_4^{(\nu, (\mu + \nu), (1+n), (c^{-\nu}, b); (p, q)}(t),$$

(2.15)

provided both sides of (2.15) exist.

2.1. Special Cases

A known result can be obtained as the special case of Theorem 2.1 [13].

Corollary 2.6. If $c > 0$, $b \geq 0$, $\delta > 0$, $\nu > 0$, $\mu > 0$, $\delta \nu - \mu > 0$, then for the solution of the equation

$$N(t) - N_0 K_4^{(\nu, \mu, \delta), (c^{-\nu}, b); (p, q)}(t) = - e^{\nu \tau} D_{\tau}^{\nu} N(t),$$

(2.1.1)

there holds the formula
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\[ N(t) = N_0 K_4^{\nu, (\mu + \nu), (\beta + 1), (\alpha - \nu), \lambda}(t), \quad (2.1.2) \]

provided both sides of (2.1.2) exist.

**Corollary 2.7.** If \( c > 0 \), \( \nu > 0 \) then for the solution of the equation

\[ N(t) - N_0 F_\nu[-c^\nu, t] = -\sum_{r=1}^{n} \binom{n}{r} c^r \nu \partial_t^{-r\nu} N(t), \quad (2.1.3) \]

there holds the formula

\[ N(t) = N_0 t^{-\nu - 1} E_{\nu, \nu+1}(-c\nu t^\nu). \quad (2.1.4) \]

If we take \( n = 1 \) in the above equation (2.1.3), we obtain the following knowing result given by the Saxena, Mathai and Haubold [16].

If \( c > 0 \), \( \nu > 1 \) then for the solution of the equation

\[ N(t) - N_0 F_\nu[-c^\nu, t] = -c^\nu \partial_t^{-\nu} N(t), \quad (2.1.5) \]

there holds the formula

\[ N(t) = N_0 t^{-\nu - 1} E_{\nu, \nu}(-c\nu t^\nu) + E_{\nu, \nu}(-c\nu t^\nu). \quad (2.1.6) \]

3. Conclusion

In this paper, we have derived a solution of generalized fractional kinetic equation in terms of the Bessel-Mitland function by the use of Laplace transform technique. The solution of fractional kinetic equations in the series forms of the \( K_4 \)-function is also discussed.

**References**

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