On decay rate of quenching profile at space infinity for axisymmetric mean curvature flow

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Abstract

We study the motion of noncompact hypersurfaces moved by their mean curvature obtained by a rotation around x-axis of the graph of a function $y = u(x, t)$ (defined for all $x \in \mathbb{R}$). We are interested to estimate its profile when the hypersurface closes open ends at the quenching (pinching) time $T$. We estimate its profile at the quenching time from above and below. We in particular prove that $u(x, T) \sim |x|^{-a}$ as $|x| \to \infty$ if $u(x, 0)$ tends to its infimum with algebraic rate $|x|^{-2a}$ (as $|x| \to \infty$ with $a > 0$).

1 Introduction and main theorem

This is a continuation of our study [4] on motion of noncompact axisymmetric $n$-dimensional hypersurface $\Gamma_t$ moved by its mean curvature. Let $\Gamma_t$ be given by a rotation of the graph of a function $y = u(x, t)$ (defined on $x \in \mathbb{R}$) around the $x$-axis (cf [1, 2]). In our previous paper [4], among other results, we have proved that if $u(x, 0) \to m := \inf_{x \in \mathbb{R}} u(x, 0) > 0$ as $|x| \to \infty$, then $\Gamma_t$ closes open ends at the time $T(m)$, where $T(m)$ is the quenching (pinching) time of the regular cylinder with radius $m$. (Moreover, there is no neck-pinch in $\mathbb{R}$ at $t = T(m)$.) These results imply that

$$\lim_{x \to \infty} u(x, T(m)) = 0 \quad \text{or} \quad \lim_{x \to -\infty} u(x, T(m)) = 0,$$

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but it does not provide the convergence rate.

We are interested in studying the profile of $u(x, T(m))$, especially the behavior as $|x| \to \infty$ which is affected by initial data.

The equation for $u$ is of the form

$$u_t = \frac{u_{xx}}{1 + u_x^2} - \frac{n-1}{u}, \quad x \in \mathbb{R}, \ t > 0$$  \hspace{1cm} (1)

supplemented by initial data

$$u(x, 0) = u_0(x) > 0, \quad x \in \mathbb{R}. \hspace{1cm} (2)$$

The function $u_0$ is assumed to satisfy

- $u_0$ is bounded and uniformly continuous in $\mathbb{R}$, \hspace{1cm} (3)
- $m := \inf_{x \in \mathbb{R}} u_0(x) > 0$. \hspace{1cm} (4)

The Cauchy problem (1)-(2) has a unique positive classical solution with the conditions (3)-(4) to the initial data (cf [4]). However, the solution quenches in finite time. For a given initial datum $u_0$, we see

$$T(u_0) = \sup\{t > 0; \inf_{x \in \mathbb{R}} u(x, t) > 0\} < \infty$$

and call it the **quenching time** of $u$. It is clear that

$$\lim_{t \to T(u_0)} \inf_{x \in \mathbb{R}} u(x, t) = 0.$$

Let $v$ be a solution of (1) with initial datum $m = \inf_{x \in \mathbb{R}} u_0(x)$. It is easily seen that

$$v' = -\frac{n-1}{v}, \ t > 0, \quad v(0) = m,$$

and

$$v(t) = \sqrt{2(n-1)(T(m) - t)} \quad \text{with} \quad T(m) = \frac{m^2}{2(n-1)}. \hspace{1cm} (6)$$

It is immediate that $T(u_0) \geq T(m)$ by a comparison argument. We treat the case $T(u_0) = T(m)$. The notion of “minimal quenching time” was defined in [4], which is recalled below.

**Definition 1.1.** *A solution of the Cauchy problem (1)-(2) is said to have a minimal quenching time, if*

$$T(u_0) = T(m).$$
In [4] we characterized solutions of (1)-(2) quenching only at space infinity. The following conditions on initial data \( u_0 \) play essential roles in [4].

A. There exists a sequence \( \{x_k\} \subset \mathbb{R} \) such that \( x_k \to \infty \) and \( u_0(x + x_k) \to m \) a.e. in \( \mathbb{R} \) as \( k \to \infty \).

B. There exists a sequence \( \{x_k\} \subset \mathbb{R} \) such that \( x_k \to -\infty \) and \( u_0(x + x_k) \to m \) a.e. in \( \mathbb{R} \) as \( k \to \infty \).

For an initial datum satisfying (3)-(4), we proved in [4] the following results for the Cauchy problem (1)-(2):

1. A solution of (1)-(2) has a minimal quenching time, if and only if the conditions A or B holds.

Moreover, if \( u_0 \) is not constant as well as the conditions A or B holds, then:

2. For an initial datum satisfying \( u_0 \neq m \), the solution (1)-(2) quenches only at space infinity.

3. There exists a function \( u(\cdot, T(m)) \in C^\infty(\mathbb{R}) \) such that \( u(\cdot, t) \to u(\cdot, T(m)) \) in the Frechét space \( C^\infty(\mathbb{R}) \) as \( t \to T(m) \), \( u(x, T(m)) > 0 \) in the whole \( \mathbb{R} \) and

\[
\liminf_{x \to -\infty} u(x, T(m)) = 0 \quad \text{or} \quad \liminf_{x \to -\infty} u(x, T(m)) = 0.
\]

For a solution \( u \) of (1)-(2) with minimal quenching time \( T(m) \), we call \( u(\cdot, T(m)) \) the profile of \( u \) (at the quenching time \( T(m) \)). The hypersurface corresponding to \( u(\cdot, T(m)) \) is called limit surface.

These are related studies on blow-up at infinity for the reaction-diffusion equations [8, 5, 6, 3, 10, 9, 11] (see also [7]). We shall explain these papers at the end of this introduction. In particular, blow-up profile was discussed, for example, in [8] and [11] for a semilinear heat equation.

In this paper we consider the relation between the profile of a quenching solution at quenching time \( T(m) \) and the form of initial data. Our goal, which is investigating the shape of limit surface, is similar to studying blow-up profile. Inspired by the method used in [8, §2b] and [11, Theorems 1.3 and 1.5], we construct a subsolution and a supersolution of the form \( \varphi(T(m) - t + g(x, t)) \) with some function \( g(x, t) \) decaying to zero at space infinity, where

\[
\varphi(s) = v(T(m) - s) = \sqrt{2(n - 1)s}, \tag{7}
\]
in order to estimate the profile at the quenching time. Let \( \psi(x) \) be a positive function satisfying the following conditions:

\[
\sqrt{\psi(x)} \text{ is bounded and uniformly continuous in } \mathbb{R}; \\
\psi(x) > 0 \text{ for } x \in \mathbb{R}; \\
\lim_{x \to \infty} \psi(x) = 0 \text{ or } \lim_{x \to -\infty} \psi(x) = 0; \\
\]

there exist constants \( C_1 > 0 \) and \( C_2 > 0 \) such that

\[
\psi(x) \leq C_1 \max\{\inf_{z \in [x-1,x]} \psi(z), \inf_{z \in [x,x+1]} \psi(z)\} \text{ for } x \in \mathbb{R}; \\
\psi(x - y) \leq C_2 \exp\left(a|y|^2\right) \psi(x) \text{ for } x, y \in \mathbb{R}, \ a \in \left(0, \frac{1}{4T(m)}\right). \\
\]

**Example 1.2.** The functions \( \psi(x) = (|x|^2 + 1)^{-b/2}, e^{-b|x|} \text{ and } (\log(|x| + e))^{-b} \) with \( b > 0 \) satisfy (8)-(12).

**Theorem 1.3.** Let \( \psi \) be a function satisfying (8)-(12). Assume that (3)-(4) hold and that there exist constants \( C_I > 0 \) and \( C_{II} > 0 \) such that

\[
u_0^2(x) - m^2 \geq C_I \psi(x) \quad (\text{or } \leq C_{II} \psi(x)). \\
\]

Then there exists \( C = C(C_I, C_2, a, T(m), C_I) > 0 \) (or \( C' = C'(C_I, C_2, a, T(m), C_{II}) > 0 \)) such that the solution of the Cauchy problem (1)-(2) satisfies

\[
u(x, T(m)) \geq C \sqrt{\psi(x)} \quad (\text{or } \leq C' \sqrt{\psi(x)}). \\
\]

By setting \( \psi(x) = \langle x \rangle^{-2a_1} \) (or \( \langle x \rangle^{-2a_2} \)) with \( \langle x \rangle = (1 + |x|^2)^{1/2} \), we obtain algebraic decay at the space infinity.

**Corollary 1.4.** Assume that there exist constants \( a_1 > 0, a_2 > 0, C_I > 0 \) and \( C_{II} > 0 \) such that

\[
u_0^2(x) - m^2 \geq C_I \langle x \rangle^{-2a_1} \quad (\text{or } \leq C_{II} \langle x \rangle^{-2a_2}). \\
\]

Then there exists \( C = C(a_1, T(m), C_I) > 0 \) (or \( C' = C'(a_2, T(m), C_{II}) > 0 \)) such that

\[
u(x, T(m)) \geq C \langle x \rangle^{-a_1} \quad (\text{or } \leq C' \langle x \rangle^{-a_2}). \\
\]

We conclude this introduction by giving a short review on blow-up (or quenching) at the space infinity. Lacey [8] considered problems in a half line of \( u_t = u_{xx} + f(u) \) in \( \mathbb{R}^+ = \{ x : x > 0 \} \) and constructed solutions blowing up only at space infinity. Gladkov [7] studied problems of the equation
\[ u_t = u_{xx} + f(x, t, u) \] in \( \mathbb{R}^+ \) and showed that solutions of the problem uniformly converge as \( x \to \infty \) to the solution of the ODE obtained by dropping \( u_{xx} \) in the equation.

Giga-Umeda [5] proved that blow-up only at space infinity occurs under the condition \( \lim_{|x| \to \infty} u_0(x) = \sup_{x \in \mathbb{R}} u_0(x) =: M \) and \( u_0 \not\equiv M \) for nonnegative solutions of \( u_t = \Delta u + u^p \) in \( \mathbb{R}^n \) (cf. also [12] for a related study). For generalization, see [6] and a review article by Giga-Seki-Umeda [3]. More recently, Shimojō [11] discussed blow-up profile \( u(x, T) := \lim_{t \to T} u(x, t) \) for \( x \in \mathbb{R}^n \). See also Seki-Suzuki-Umeda [10] and Seki [9] for quasilinear parabolic equations, which generalized the result of [6]. They also gave necessary and sufficient conditions for a solution to have “minimal blow-up time (or the least blow-up time)”. See [9, 10, 3] for the precise definition of the last notion.

2 Profile at quenching

In order to prove Theorem 1.3, we construct a subsolution and supersolution of the form \( \phi(T(m) - t + g(x, t)) \), as we have explained before. This is a modification of the method employed in [8] and [11] to study blow-up profile for a semilinear heat equation. The function

\[ g(x, t) = \int_{-\infty}^{\infty} G(x - y, t)\psi(y)dy \]

with the Gauss kernel of heat equation

\[ G(x, t) = (4\pi t)^{-1/2} \exp \left( -\frac{x^2}{4t} \right) \]

is used there. However, because the problem which we treat here is a quasilinear equation, the Gauss kernel is not appropriate in our problem. We use the following function instead of \( G(x, t) \):

\[ g_{\alpha, \beta}^{\gamma}(x, t) = g_{\alpha, \beta}^{\gamma, \psi}(x, t) = \int_{-\infty}^{\infty} G_{\alpha, \beta}^{\gamma}(x - y, t)\psi(y)dy, \quad (15) \]

where

\[ G_{\alpha, \beta}^{\gamma}(x, t) = \frac{|x|^{\beta}}{(t + \gamma)^{\alpha}} \exp \left( -\frac{x^2}{4(t + \gamma)} \right) \]

with \( \alpha \geq 0, \beta \geq 0 \) and \( \gamma > 0 \) being constants. Note that this \( g_{\alpha, \beta}^{\gamma} \) may be expressed by

\[ g_{\alpha, \beta}^{\gamma}(x, t) = \int_{-\infty}^{\infty} G_{\alpha, \beta}^{\gamma}(y, t)\psi(x - y)dy. \]
It is easily seen that the derivatives are calculated and estimated as follows:

\[
|\partial_x g_{\alpha,0}^\gamma| \leq \frac{g_{\alpha+1,1}^\gamma}{2}, \tag{16}
\]

\[
\partial_{xx} g_{\alpha,0}^\gamma = \frac{g_{\alpha+2,2}^\gamma}{4} - \frac{g_{\alpha+1,0}^\gamma}{2}, \tag{17}
\]

\[
\partial_t g_{\alpha,0}^\gamma = \frac{g_{\alpha+2,2}^\gamma}{4} - \alpha g_{\alpha+1,0}^\gamma. \tag{18}
\]

and

\[
g_{\alpha,\beta}^\gamma(x, t) = g_{0,\beta}^\gamma(t + \gamma)^\alpha. \tag{19}
\]

Before proving the Theorem 1.3 we prepare two propositions.

**Proposition 2.1.** Let \( \psi \) be a positive bounded uniformly continuous function. For any \( C > 0 \) and \( \gamma > 0 \) the function

\[
W(x, t) = \phi(T(m) - t + Cg_{0,0}^\gamma(x, t)) \tag{20}
\]

is a supersolution of (1) in \( \mathbb{R} \times (0, T(m)) \), where \( \phi \) is defined in (7).

**Proof.** By a direct calculation we have

\[
W_t - \frac{W_{xx}}{1 + W_x^2} + \frac{n - 1}{W} \geq -\phi' + C\phi' \partial_t g_{0,0}^\gamma - \frac{C\phi' \partial_{xx} g_{0,0}^\gamma + (C\partial_x g_{0,0}^\gamma)^2 \phi''}{1 + (C\phi' \partial_x g_{0,0}^\gamma)^2} + \frac{n - 1}{\phi}.
\]

Noting that \( \phi' \partial_t g_{0,0}^\gamma \geq 0 \) from (18) and \( \phi' = (n - 1)/\phi \), we obtain

\[
W_t - \frac{W_{xx}}{1 + W_x^2} + \frac{n - 1}{W} \geq \frac{C\phi' \partial_t g_{0,0}^\gamma - C\phi' \partial_{xx} g_{0,0}^\gamma - (C\partial_x g_{0,0}^\gamma)^2 \phi''}{1 + (C\phi' \partial_x g_{0,0}^\gamma)^2}.
\]

Since \( (\partial_t - \partial_{xx}) g_{0,0}^\gamma = g_{1,0}^\gamma/2 \) by (17)-(18), we have

\[
W_t - \frac{W_{xx}}{1 + W_x^2} + \frac{n - 1}{W} \geq \frac{1}{1 + (C\phi' \partial_x g_{0,0}^\gamma)^2} \left( \frac{C\phi' g_{1,0}^\gamma}{2} - (C\partial_x g_{0,0}^\gamma)^2 \phi'' \right).
\]

Due to the fact that \( \phi'' \leq 0 \), we see that \( W \) is a supersolution of (1). \( \square \)
Proposition 2.2. Assume that $\psi$ is a function satisfying (8)-(12) and

$$\gamma \in \left( 0, \frac{1}{a} - 4T(m) \right) \quad (21)$$

with the constant $a$ in (12). Then, for each constant $C > 0$, the function

$$w(x, t) = \phi(T(m) - t + Cg_{\alpha, \beta}^\gamma(x, t)) \quad (22)$$

is a subsolution of (1) in $\mathbb{R} \times (0, T(m))$ provided that $\alpha$ satisfies $\alpha \geq \alpha_0$ with some constant $\alpha_0 = \alpha_0(C_1, C_2, a, T(m), \gamma) > 0$, where $\phi$ is the function defined in (7).

Before proving Proposition 2.2, we prepare a lemma on estimates for $g_{\alpha, \beta}^\gamma$.

Lemma 2.3. Assume the same hypotheses as in Proposition 2.2. Then for $\beta = 0, 1, 2$, there exist constants $C_3 = C_3(C_1, \gamma) > 0$ and $C_4 = C_4(C_2, a, T(m), \gamma) > 0$ such that

$$C_3 \psi(x) \leq g_{\alpha, \beta}^\gamma(x, t) \leq C_4 \psi(x) \quad \text{in} \ \mathbb{R} \times [0, T(m)],$$

where $C_1$ and $C_2$ are the constants in (11) and (12), respectively.

Proof. First we show $g_{\alpha, \beta}^\gamma \geq C_3 \psi(x)$ with some $C_3 > 0$. From (11)

$$\psi(x) \leq C_1 \inf_{z \in [x-1, x]} \psi(z) \quad (23)$$

or

$$\psi(x) \leq C_1 \inf_{z \in [x, x+1]} \psi(z) \quad (24)$$

for each $x \in \mathbb{R}$. If (23) holds, then there exists a constant $C_3 > 0$ such that

$$g_{\alpha, \beta}^\gamma(x, t) \geq \inf_{z \in [x-1, x]} \psi(z) \times \int_0^1 |y|^\beta \exp \left( -\frac{|y|^2}{4\gamma} \right) dy$$

$$\geq \psi(x) \frac{1}{C_1} \int_0^1 |y|^\beta \exp \left( -\frac{|y|^2}{4\gamma} \right) dy.$$

Set

$$C_3 = \min_{\beta=0,1,2} \frac{1}{C_1} \int_0^1 |y|^\beta \exp \left( -\frac{|y|^2}{4\gamma} \right) dy = \frac{1}{C_1} \int_0^1 |y|^2 \exp \left( -\frac{|y|^2}{4\gamma} \right) dy.$$

We then see that

$$g_{\alpha, \beta}^\gamma(x, t) \geq C_3 \psi(x).$$
A similar argument shows that if (24) holds, then
\[ g_{0,\beta}^\gamma(x, t) \geq C_3 \psi(x). \]
Thus we see that
\[ g_{0,\beta}^\gamma(x, t) \geq C_3 \psi(x) \]
for any \( x \in \mathbb{R} \).
We next prove \( g_{0,\beta}^\gamma(x, t) \leq C_4 \psi(x) \) with some \( C_4 > 0 \). For (21) it is possible to take a constant \( \gamma > 0 \) depending only \( a \) and \( m \) that satisfies
\[ \frac{1}{4(T(m) + \gamma)} - a > 0. \]
Thus we see that from (12)
\[ g_{0,\beta}^\gamma(x, t) \leq C_2 \psi(x) \int_{-\infty}^{\infty} |y|^\beta \exp \left\{ - \left( \frac{1}{4(T(m) + \gamma)} - a \right) |y|^2 \right\} dy \]
for \( t \in [0, T(m)] \). Let
\[ C_4 = \max_{\beta=0,1,2} C_2 \int_{-\infty}^{\infty} |y|^\beta \exp \left\{ - \left( \frac{1}{4(T(m) + \gamma)} - a \right) |y|^2 \right\} dy. \]
Then we see
\[ g_{0,\beta}^\gamma(x, t) \leq C_4 \psi(x) \]
for \( t \in [0, T(m)] \).

**Proof of Proposition 2.2.** As before, for \( \phi = \phi(T(m) - t + Cg_{\alpha,0}^\gamma(x, t)) \) we have
\[
\begin{align*}
\frac{w_t - w_{xx}}{1 + w_x^2} &+ \frac{n - 1}{w} \\
&= -\phi' + C\phi' \partial_\alpha g_{\alpha,0}^\gamma - \frac{C\phi' \partial_{xx} g_{\alpha,0}^\gamma + (C\partial_x g_{\alpha,0}^\gamma)^2 \phi''}{1 + (C\phi' \partial_x g_{\alpha,0}^\gamma)^2} + \frac{n - 1}{\phi} \\
&\leq \frac{C(n - 1)\partial_\alpha g_{\alpha,0}^\gamma}{\phi} + \frac{C(n - 1) |\partial_{xx} g_{\alpha,0}^\gamma|}{\phi} + \frac{\{C(n - 1)\partial_x g_{\alpha,0}^\gamma\}^2}{\phi^3} \\
&\quad \text{(25)}
\end{align*}
\]
by using the fact that \( \phi' = (n - 1)/\phi \) and \( \phi'' = -(n - 1)^2/\phi^3 \). It is easily seen that
\[
\phi^2 = 2(n - 1)(T(m) - t + Cg_{\alpha,0}^\gamma) \geq 2(n - 1)(Cg_{\alpha,0}^\gamma). \quad \text{(26)}
\]
From Lemma 2.3, (16), (19) and (26), it follows that
\[
\frac{\partial_x g_{\alpha,0}^\gamma}{\phi^2} \leq \frac{g_{0,1}^{\gamma}}{4(n - 1)(t + \gamma)g_{0,0}^\gamma} \leq \frac{C_4}{4\gamma(n - 1)CC_3}.
\]
(27)

Substituting (27) for (25), and using (17)-(19), we have
\[
w_t - \frac{w_{xx}}{1 + w_x^2} + \frac{n - 1}{w} \leq \frac{C(n - 1)}{2(t + \gamma)^a + 2\phi} \left[ g_{0,2}^{\gamma} + (t + \gamma) \left\{ -2\alpha g_{0,0}^{\gamma} + g_{0,0}^{\gamma} + \frac{C_4 g_{0,1}^{\gamma}}{4C_3} \right\} \right]
\leq \frac{C(n - 1)}{2(t + \gamma)^a + 2\phi} \left[ -2\alpha C_3 + C_4 \left\{ 1 + (T(m) + \gamma) \left( 1 + \frac{C_4}{4C_3} \right) \right\} \right]
\]
in \(\mathbb{R} \times [0, T(m)]\). If \(\alpha\) satisfies
\[
\alpha \geq \alpha_0 \equiv \frac{C_4}{2\gamma C_3} \left\{ 1 + (T(m) + \gamma) \left( 1 + \frac{C_4}{4C_3} \right) \right\},
\]
(28)
then \(w\) is a subsolution of (1) in \(\mathbb{R} \times (0, T(m))\).

Proof of Theorem 1.3. There exist positive constants \(c_1 = c_1(C_2, a, \gamma, \alpha)\) and \(c_2 = c_2(C_1, \gamma)\) such that
\[
g_{0,0}^{\gamma}(x, 0) \leq c_1 \psi(x), \quad g_{0,0}^{\gamma}(x, 0) \geq c_2 \psi(x)
\]
by Lemma 2.3 and (19), and thus
\[
u_0^2(x) \geq m^2 + C_1 g_{0,0}^{\gamma}(x, 0) \quad \text{(or } \leq m^2 + C_h g_{0,0}^{\gamma}(x, 0)\text{)}
\]
with \(C_1 = C_1/c_1\) (or \(C_h = C_{II}/c_2\)).

Since \(m^2 = 2(n - 1)T(m)\) by (6), we have
\[
u_0(x) \geq \sqrt{2(n - 1)T(m) + C_1 g_{0,0}^{\gamma}(x, 0)} \geq w(x, 0)
\]
\corr{\text{or } \leq \sqrt{2(n - 1)T(m) + C_h g_{0,0}^{\gamma}(x, 0)} \leq W(x, 0)}\)

Propositions 2.1, 2.2 and the comparison principle yield
\[
u(x, t) \geq w(x, t) \quad \text{(or } \leq W(x, t)\text{)} \quad \text{in } \mathbb{R} \times [0, T(m)].
\]

We thereby get
\[
u(x, T(m)) \geq \sqrt{C_1 g_{0,0}^{\gamma}(x, T(m))} \quad \text{(or } \leq \sqrt{C_h g_{0,0}^{\gamma}(x, T(m))} \text{)}.
\]
By using Lemma 2.3 and letting \( C = \sqrt{C_1 C_3} \) and \( C' = \sqrt{C_h C_4} \), we obtain
\[
u(x, T(m)) \geq C \psi^{1/2}(x) \quad \text{(or) \quad \leq C' \psi^{1/2}(x)}.
\]

We may choose
\[
\gamma = \frac{1}{2a} - 2T(m), \quad \alpha = \alpha_0
\]
with \( \alpha_0 \) in (28), and then the constant \( C \) (or \( C' \)) depends only on \( C_1, C_2, a, T(m), C_I \) (or \( C_1, C_2, a, T(m), C_{II} \)). \( \square \)

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