

Process and finned tube for the thermal cracking of
hydrocarbons

- 5 The invention relates to a process and a finned tube
for the thermal cracking of hydrocarbons in the
presence of steam, in which the charge mixture is
passed through externally heated tubes with helical
inner fins.
- 10 Tube furnaces in which a hydrocarbon/steam mixture is
passed through series of individual or meandering tubes
(cracking tube coils) at temperatures of above 750°C
made from heat-resistant chromium-nickel-steel alloys
with a high resistance to oxidation or scaling and a
15 high resistance to carburization have proven suitable
for the high-temperature pyrolysis of hydrocarbons
(crude oil derivatives). The tube coils comprise
vertically running, straight tube sections which are
connected to one another via U-shaped tube bends or are
20 arranged in parallel with one another; they are usually
heated with the aid of side-wall burners and in some
cases also with the aid of bottom burners and therefore
have what is known as a light side, facing the burners,
and what is known as a dark side, which is offset by
25 90° with respect thereto, i.e. runs in the direction of
the rows of tubes. The mean tube metal temperatures
(TMT) are in some cases over 1000°C.
- 30 The service life of the cracking tubes is dependent to
a very significant extent on the creep resistance and
the carburization resistance, and also the coking rate,
of the tube material. A crucial factor for the coking
rate, i.e. the growth of a layer of carbon deposits
(pyrolysis coke) on the tube inner wall is, in addition
35 to the type of hydrocarbons used, the cracking gas
temperature in the region of the inner wall and what is
known as the operating severity, which conceals the
influence of the system pressure and the residence time
in the tube system on the ethylene yield. The operating

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severity is set on the basis of the mean outlet temperature of the cracking gases (e.g. 850°C). The higher the gas temperature in the vicinity of the tube inner wall above this temperature, the more extensive the growth of the layer of pyrolysis coke becomes, and the insulating action of this layer allows the tube metal temperature to increase still further. Although the chromium-nickel-steel alloys containing 0.4% of carbon, over 25% of chromium and over 20% of nickel, for example 35% of chromium, 45% of nickel and if appropriate 1% of niobium, that are used as tube material have a high resistance to carburization, the carbon diffuses into the tube wall at defects in the oxide layer, where it leads to considerable carburization which can amount to carbon contents of from 1% to 3% at wall depths of 0.5 to 3 mm. This is associated with considerable embrittlement of the tube material, with the risk of crack formation in the event of fluctuating thermal loads, in particular when the furnace is being started up and shut down.

To break down the carbon deposits (coking) on the tube inner wall, it is necessary for cracking operation to be interrupted from time to time and for the pyrolysis coke to be burnt with the aid of a steam/air mixture. This requires operation to be interrupted for up to 36 hours, and therefore has a considerable adverse effect on the economics of the process.

It is also known from GB Patent 969 796 to use cracking tubes with inner fins. Although inner fins of this type result in an internal surface area which is a good few percent, for example 10%, larger, with a corresponding improvement in the heat transfer, they are also associated with the drawback of a considerably increased pressure loss compared to a smooth tube, on account of friction at the enlarged tube inner surface. The higher pressure loss requires a higher system pressure, which inevitably changes the residence time

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and has an adverse effect on the yield. An additional factor is that the known tube materials with high carbon and chromium contents can no longer be profiled by cold-working, for example cold-drawing. They have the drawback that their deformability decreases greatly as the hot strength rises. This has led to the high tube metal temperatures of, for example, up to 1050°C, which are desirable with regard to the ethylene yield, requiring the use of centrifugally cast tubes. However, since centrifugally cast tubes can only be produced with a cylindrical wall, special shaping processes are required, for example removal of material by electrolytic machining or a shaping welding process if internally finned tubes are to be produced.

In view of this background, the invention is based on the problem of improving the economics of the thermal cracking of hydrocarbons in tubular furnaces with externally heated tubes having helical inner fins.

This object is achieved by a process in which a swirling flow is generated in the immediate vicinity of the fins of preferably a centrifugally cast tube and this swirling flow is converted into a core zone with a predominantly axial flow at increasing radial distance from the fins. The transition between the outer zone with the swirling flow and the core zone with the predominantly axial flow is gradual, for example parabolic.

In the process according to the invention, the swirling flow takes up the detaching turbulence at the fin flanks, so that the turbulence is not locally recycled in the form of a continuous circulating flow into the fin valleys. Despite the obviously longer distances covered by the particles through the spiral paths, the mean residence time is lower than in a smooth tube and, moreover, more homogeneous over the cross section (cf. Fig. 7). This is confirmed by the higher overall

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velocity in the profiled tube with swirl (profile 3) compared to the tube with straight fins (profile 2). This is ensured in particular if the swirling flow in the region of the fins or the fins run at an angle of
5 20° to 40°, for example 30°, preferably 25 to 32.5°, with respect to the tube axis.

In the process according to the invention, the heat supply, which inevitably differs over the tube
10 circumference between the light side and the dark side, is compensated for in the tube wall and the tube interior, and the heat is rapidly dissipated inward to the core zone. This is associated with a reduction in the risk of local overheating of the process gas at the
15 tube wall, with the resultant formation of pyrolysis coke. Moreover, the thermal loading on the tube material is lower on account of the temperature compensation between the light side and the dark side, which lengthens the service life. Finally, in the
20 process according to the invention, the temperature is also made more uniform over the tube cross section, resulting in an improved olefin yield. The reason for this is that without the radial temperature compensation according to the invention in the tube
25 interior, over-cracking would occur at the hot tube wall and recombination of cracking products would occur in the center of the tube.

Furthermore, a laminar flow layer, which is
30 characteristic of turbulent flows, with a greatly reduced heat transfer is formed in the case of a smooth tube and to a greater extent in the case of fin profiles with an internal circumference which is increased by more than 5%, for example 10%, by fins.
35 This laminar flows leads to the increased formation of pyrolysis coke, likewise with a poor thermal conductivity. The two layers together require greater introduction of heat or a higher burner capacity. This increases the tube metal temperature (TMT) and

correspondingly shortens the service life.

The invention avoids this by virtue of the fact that the inner circumference of the profile amounts to
5 around at most 5%, for example 4% or even 3.5%, with respect to the circumference of the envelope circle touching the fin valleys. However, the internal circumference may also be up to 2% smaller than the envelope circle. In other words, the relative profile
10 circumference amounts to at most 1.05 to 0.98% of the envelope circle circumference. Accordingly, the difference in area of the profile tube according to the invention, i.e. its laid-out internal surface area, with respect to a smooth tube having the envelope
15 circle diameter, amounts to at most +5% to -2% or 1.05 to 0.98 times the area of the smooth tube.

The tube profile according to the invention allows a lower tube density (kg/m) compared to a finned tube in
20 which the internal circumference of the profile is at least 10% greater than the circumference of the envelope circle. This is demonstrated by a comparison between two tubes with the same hydraulic diameter and accordingly the same pressure loss and the same thermal
25 result.

A further advantage of the profile circumference according to the invention (relative profile circumference) with respect to the envelope circle
30 circumference is more rapid heating of the charge gas at a reduced tube metal temperature.

The swirling flow according to the invention very considerably reduces the extent of the laminar layer;
35 moreover, it is associated with a velocity vector directed toward the center of the tube, which reduces the residence time of cracking radicals and/or cracking products at the hot tube wall and the chemical and catalytic decomposition thereof to form pyrolysis coke.

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In addition, the temperature differences between fin valleys and fins, which are not inconsiderable in the case of internally profiled tubes with high fins, are compensated for by the swirling flow according to the invention. This increases the time between two coke-removal operations being required. Without the swirling flow according to the invention, a not inconsiderable temperature difference results between the fin peaks and the base of the fin valleys. The residence time of the cracking products which tend to coke is shorter in the case of cracking tubes provided with helical inner fins. This is dependent on the nature of the fins in the individual circumstances.

15 In the diagram:

The upper curve shows:	profile 6: 16° pitch
The middle curve shows:	profile 3: 30° pitch
The lower curve shows:	profile 4: 3 fins with a 30° pitch.

The curves clearly demonstrate that the higher circumferential velocity of the profile 6 with 4.8 mm high fins is consumed within the fin valleys, whereas the circumferential velocity of the profile according to the invention with a fin height of just 2 mm penetrates into the core of the flow. Although the circumferential velocity of the profile 4 with just 3 fins is approximately as high, it does not effect any spiral acceleration of the core flow.

According to the curves shown in the diagram presented in Fig. 2, the profile according to the invention effects a spiral acceleration in the fin valleys (upper branch of the curve) which covers wide areas of the tube cross-section and is therefore responsible for homogenizing the temperature in the tube. The lower circumferential velocity at the fin peaks (lower branch

of the curve), furthermore, ensures that no turbulence and back-flows occur.

Fig. 3 illustrates three test tubes, including their data, in cross section; these tubes include the profile 3 according to the invention. The diagrams each indicate the temperature profile across the tube radius on the dark side and the light side. A comparison of the diagrams reveals the lower temperature difference between tube wall and tube center and the lower gas temperature at the tube wall in the case of the profile 3 in accordance with the invention.

The swirling flow according to the invention ensures that the fluctuation in the inner-wall temperature over the circumference of the tube, i.e. between the light side and the dark side, is less than 12°C , even though the tube coils, which are customarily arranged in parallel rows, of a tube furnace are heated or acted on by combustion gases with the aid of side wall burners only on opposite sides and the tubes therefore each have a light side, facing the burners, and a dark side, which is offset through 90° with respect thereto. The mean tube metal temperature, i.e. the difference in the tube metal temperature on the light side and the dark side, leads to internal stresses and therefore determines the service life of the tubes. Therefore, the reduction in the mean tube metal temperature of a tube according to the invention with eight fins with a pitch of 30° , a tube internal diameter of 38.8 mm and a tube external diameter of 50.8 mm, i.e. a difference in height between fin valleys and fin peaks of 2 mm of 11° compared to a smooth tube of the same diameter, based on a mean service life of 5 years, which can be seen from the diagram presented in Fig. 4, results, at an operating temperature of 1050°C , in a calculated increase in service life to approximately 8 years.

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The temperature distribution between the light side and the dark side for the three profiles shown in Fig. 3 is to be found in the diagram shown in Fig. 5. The lower level of the temperature curve for the profile 3 compared to the smooth tube (profile 0) and the considerably narrower fluctuation range for the profile 3 curve compared to the profile 1 curve are noticeable.

A particularly expedient temperature distribution is established if the isotherms run in a spiral shape from the tube inner wall to the core of the flow.

A more uniform distribution of the temperature over the cross section results in particular if the circumferential velocity is built up within 2 to 3 m and then remains constant over the entire length of the tube.

With a view to achieving a high olefin yield with a relatively short tube length, the process according to the invention should be operated in such a way that the temperature homogeneity factor over the cross section and the temperature homogeneity factor referenced on the hydraulic diameter is over 1 in relation to the homogeneity factor of a smooth tube (H_{G0}). In this context, the homogeneity factors are defined as follows:

$$H_{G0}[-]H_{P0} = \Delta T_0 \cdot d_x / \Delta T_x \cdot d_0$$

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The flow configuration according to the invention comprising core flow and swirling flow can be achieved with a finned tube in which the flank angle of the fins, which are in each case continuous over the length of a tube section, i.e. the external angle between the fin flanks and the radius of the tube, is 16° to 25°, preferably 19° to 21°. A flank angle of this type, in particular in combination with a fin pitch of from 20° to 40°, for example 22.5° to 32.5°, ensures that what

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results in the fin valleys is not a more or less continuous swirling flow which returns to the fin valleys behind the fin flanks and leads to the formation of undesirable "twisters" in the fin valleys.

5 Rather, the turbulence formed in the fin valleys become detached from the fin flanks and are taken up by the swirling flow. The swirl energy induced by the fins accelerates the gas particles and leads to a higher overall velocity. This leads to a reduction in the tube
10 metal temperature, and also makes the latter more uniform, as well as making the temperature and the residence time across the tube cross section more uniform.

15 The nature of the finned tube according to the invention can be seen from the illustration of a tube segment in Fig. 6 and the associated characteristic parameters

- 20 - Hydraulic diameter D_h in mm, $R_i \leq D_h/2$
- Flanked angle β
- Fin height H
- Envelope circle radius $R_a = R_i + H$ and $D_a = 2 \times R_a$
- Center angle α
- 25 - Radius of curvature $R = R_a (\sin \alpha/2 \sin \beta + \sin \alpha)$
- Envelope circle circumference $2\pi R_a$
- Angle in the oblique-angled triangle $\gamma = 180 - (\alpha + \beta)$
- Internal radius $R_i = 2R (\sin \gamma / \sin \alpha) - R$
- Fin height $H = R_a - R_i$
- 30 - Profile circumference $U_p = 2 \times \text{number of fins} \times \pi R / 180 (2\beta + \alpha)$
- Fin surface area F_R
- Area of the envelope circle $F_a = \pi D_a^2 / 4$
- Area of the inner circle $F_i = \pi \cdot D_i$
- 35 - Profile area within the envelope circle $F_p = F_R \cdot \text{number of fins}$
- Profile circumference $U_p = (1.05 \text{ to } 0.98) \cdot 2\pi R_a$

The fins and the fin valleys which are located between the fins may be of mirror-symmetrical design in cross section and adjoin one another or may form a wave line with in each case the same radii of curvature. The flank angle then results between the tangents of the two radii of curvature at the contact point and the radius of the tube. In this case, the fins are relatively shallow; fin height and flank angle are matched to one another in such a way that the hydraulic diameter of the profile from the ratio $4 \times \text{clear cross section} / \text{profile circumference}$ is greater than or equal to the inner circle of the profile. The hydraulic diameter is therefore in the inner third of the profile height. Consequently, the fin height and the number of fins increase as the diameter becomes greater, so that the swirling flow is maintained in the direction and intensity required for the action of the profile.

A greater flow velocity (Fig. 2) results between the fins or in the fin valleys, leading to a self-cleaning effect, i.e. to a reduction in the amounts of pyrolysis coke that is deposited.

If the fins are produced by build-up welding or overlay welding using a centrifugally cast tube, the tube wall between the individual fins remains substantially unchanged, so that the fin valleys lie on a common circle which corresponds to the internal circumference of the centrifugally cast tube.

Tests have shown that - irrespective of the internal diameter of the tubes - a total of 8 to 12 fins are sufficient to achieve the flow configuration according to the invention.

In the case of the finned tube according to the invention, the ratio of the quotients of the heat transfer coefficients Q_R/Q_0 to the quotient of the pressures losses $\Delta P_R/\Delta P_0$ in the water test, applying and

observing the laws of similarity and using the Reynolds numbers given for a naphtha/steam mixture, is preferably from 1.4 to 1.5, where R denotes a finned tube and 0 denotes a smooth tube.

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The superiority of the finned tube according to the invention (profile 3) compared to a smooth tube (profile 0) and a finned tube with eight parallel fins (profile 1), among which the radial distance between the fin valleys and the fin peaks is 4.8 mm, is illustrated by the data presented in the table below. The finned tubes all have 8 fins and the same envelope circle.

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PROFILE	0	1	3
Fluid temp. at 9950 mm in the center T_m [°C]	843.6	848.1	843.0
Fluid temp. at 9950 mm at the edge T_r [°C]	888.9	894	874.8
Temperature range at 9950 mm $\Delta T = T_r - T_m$ [°C]	45.3	45.9	31.8
Homogeneity factor for the smooth tube H at $H_t = \Delta T_g / \Delta T_k$	1	0.9869281	1.4245283
Hydraulic diameter d_h [m]	0.0380	0.0256	0.0344
Homogeneity factor referenced on hydraulic diameter based on the smooth tube $H_{t0} : H_{t0} = \Delta T_0 \cdot d_x / \Delta T_x \cdot d_0$	1	0.8477193	1.3420556
Classification of H:	2	2	1

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In this context, the hydraulic diameter is defined as follows:

20 $D_{hydr} = 4 \times (\text{clear cross section}) / \text{internal circumference};$

it preferably corresponds to the internal diameter of a comparable smooth tube and then results in a homogeneity factor of 1.425.

25

In the water test, the finned tube according to the invention gave a heat transfer (Q_R) which was higher by a factor of 2.56 than the smooth tube, with a pressure loss (ΔP_R) which was higher only by a factor of 1.76.

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Fig. 7 compares three different profile tubes, including a tube according to the invention with 8 fins with a pitch of in each case 30° , of a tube with a smooth internal wall (smooth tube). The hydraulic diameter, the axial velocity, the residence time and the pressure loss are given for each cross section.

The starting data used were the quantitative throughputs in an operational smooth tube with an internal diameter of 38 mm, which is identical to the hydraulic diameter. Using the laws of similarity (same Reynolds numbers), these data were converted by calculation to warm water and used as the basis for the tests (cf. the ratio of the quotients for the heat transfer and the pressure loss for tests with water and the referenced homogeneity factor for the calculation using gases).

The different velocity profiles result from the same quantitative throughputs at different hydraulic diameters (reciprocal relationship).

The comparison of the velocities for the profiles 2 and 3, which are identical in cross section, illustrates the improved velocity, acceleration and residence time with the tubes according to the invention (profile 3). For the same hydraulic diameter, the velocity component in the circumferential direction, caused by the swirling induced by the fins, causes the flow to be detached from the tube wall and induces a helically rising velocity over the entire cross section.

The directed, spiral flow introduces the heat from the tube wall into the flow and therefore distributes it

more evenly than in a normal, undirected turbulent flow (smooth tube, profiles 1 and 2). The same applies to the residence time for the particles. The spiral directed flow distributes the particles more uniformly over the cross section, while the acceleration at the profile flanks reduces the mean residence time. The higher pressure loss with the profile 3 results from the circumferential velocity. In the case of profile 1, the cause is the considerable constriction of the flow and the friction loss at the large inner surface of the profile.

Depending on the material, the finned tubes according to the invention can be produced, for example, from a centrifugally cast tube by the ends of a tube with axially parallel fins being rotated with respect to one another, or by the inner profile being produced by deformation of a centrifugally cast tube, for example by hot forging, hot drawing or cold-working by means of a profiling tool, for example a flying mandrel or a mandrel rod with an outer profile which corresponds to the inner profile of the tube.

A number of variants of cutting machines for the internal profiling of tubes are known, for example from German Patent 195 23 280. These machines are also suitable for the production of a finned tube according to the invention.

In the case of hot-forming, the deformation temperature should be set in such a way that the microstructural grain is partially destroyed in the region of the internal surface, and is accordingly recrystallized at a later stage under the influence of the operating temperature. The result of this is a fine-grained microstructure which allows rapid diffusion of chromium, silicon and/or aluminum through the austenitic matrix to the inner surface of the tube,

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where an oxidic protective layer is then rapidly built up.

5 The fins according to the invention can also be produced by build-up welding; in this case, it is not possible to form a curved fin base between the individual fins, but rather the original profile of the inner wall of the tube is substantially maintained there.

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The inner surface of the tube according to the invention should have the lowest possible roughness; it can therefore be smoothed, for example mechanically polished or electrolytically levelled.

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Suitable tube materials for use in ethylene plants are iron and/or nickel alloys containing 0.1% to 0.5% of carbon, 20 to 35% of chromium, 20 to 70% of nickel, up to 3% of silicon, up to 1% of niobium, up to 5% of tungsten and additions of hafnium, titanium, rare earths or zirconium, in each case of up to 0.5%, and up to 6% of aluminum.

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Patent Claims:

1. A process for the thermal cracking of hydrocarbons in the presence of steam, in which the charge mixture is passed through externally heated tubes with helical internal fins, characterized in that a swirling flow is generated in the immediate vicinity of the fins which runs at an angle of more than 20° to 40°, with respect to the tube axis and is converted into a core zone with a predominantly axial flow at increasing radial distance from the fins.
2. The process as claimed in claim 1, characterized in that the fluctuation in the inner-wall temperature over the circumference of the tube is less than 12°C.
3. The process as claimed in claim 1 or 2, characterized in that the isotherms in the core zone run in spiral form.
4. The process as claimed in one of claims 1 to 3, characterized in that the velocity of the swirling flow is built up within the first 2 to 3 m of the length of the tube and then remains constant.
5. The process as claimed in one of claims 1 to 4, characterized in that the velocity of the swirling flow covers the entire cross section after the first 2 to 3 m of the tube length.
6. The process as claimed in one of claims 1 to 5, characterized in that the temperature homogeneity factor over the cross section and the temperature homogeneity factor referenced on the hydraulic diameter is over 1 in relation to the homogeneity factors of a smooth tube.
7. The process as claimed in one of claims 1 to 6, characterized in that the flow velocity in the boundary layer at the tube wall is 8 to 12% lower and the flow velocity in the core zone is 8 to 12% higher than in the case of a comparable tube with straight fins of the same type.
8. The process as claimed in claims 1 to 7, characterized in that the gas is accelerated, over a distance of from 100 to 200 cm, calculated from the gas inlet,

to a circumferential velocity which amounts to 15 to 20% of the axial velocity in the core zone, and in that the circumferential velocity subsequently remains constant.

9. The process as claimed in claims 1 to 8, characterized in that the sum of axial velocity and circumferential velocity is greater than the axial velocity of a comparable tube with straight fins of the same type.
10. The process as claimed in claims 1 to 9, characterized in that the gas particles are accelerated at the flanks of the fins.
11. A finned tube having a plurality of helically running inner fins, characterized in that the fins runs at an angle of more than 20° to 40° preferably of $22,5^\circ$ to $32,5^\circ$ with respect to the tube axis.
12. The finned tube as claimed in claim 11, characterized in that the profile circumference (U_p) amounts to +5 to -2% of the envelope circle touching the fin valleys.
13. The finned tube as claimed in claim 11 or 12, characterized in that the flank angle of the fins is 16° to 25° .
14. The finned tube as claimed in one of claims 11 to 13, characterized in that the fins and the valleys located between the fins are designed to be mirror-symmetrical in cross section.
15. The finned tube as claimed in one of claims 11 to 14, characterized in that the fins and the fin valleys have the same radius of curvature.
16. The finned tube as claimed in claim 11 or 15, characterized in that the fins are welded on and the fin valleys lie on a common circle.
17. The finned tube as claimed in one of claims 11 to 16, characterized by a total of 6 to 12 fins.
18. The finned tube as claimed in one of claims 11 to 17, characterized in that the hydraulic diameter of the finned tube is at least equal to the diameter of the inner circle (R_i).
19. The finned tube as claimed in one of claims 11 to 18, characterized in that the

ratio of the quotients of the heat transfer coefficients Q_R/Q_0 to the quotient of the pressure losses $\Delta P_R/\Delta P_0$ in the water test is 1.4 to 1.5, where R denotes a finned tube and 0 denotes a smooth tube.

20. The finned tube as claimed in one of claims 11 to 19, characterized in that the radius of curvature (R) of the fin cross section is 3.5 to 20 mm.
21. The finned tube as claimed in one of claims 11 to 20, characterized by a fin height (H) of 1.25 to 3 mm.
22. The finned tube as claimed in one of claims 11 to 21, characterized in that the clear cross section within the profile circumference (U_p) amounts to 85 to 95% of the area of the envelope circle (F_a).
23. The finned tube as claimed in one of claims 11 to 22, characterized in that the profile area (F_p) amounts to 40 to 50% of the annular area between the envelope circle and the inner circle.
24. A process for producing the finned tube as claimed in one of claims 11 to 23, characterized in that the ends of a tube with axially parallel fins are rotated with respect to one another.
25. A process for producing the finned tube as claimed in one of claims 11 to 24, characterized in that the inner profile is produced by deformation using a profiling tool.
26. The process as claimed in claim 25, characterized in that during the deformation the micro structural grain is partially broken up in the region of the inner surface.
27. A process for producing the finned tube as claimed in one of claims 11 to 25, characterized in that the inner profile is produced by deformation using a profiling tool or by build-up welding.
28. A process for producing a centrifugally cast tube as described in claims 11 to 23, characterized in that the inner profile is produced by electrolyte removal of material.
29. The process as claimed in one of claims 26 to 28, characterized in that the inner surface of the profiled tube is smoothed.

30. The use of a centrifugally cast tube for the production of the finned tube as claimed in one of claims 11 to 23.
31. The use as claimed in claim 30, wherein the centrifugally cast tube consists of a nickel alloy containing 0.1 to 0.5% of carbon, 20 to 35% of chromium, 20 to 70% of nickel, up to 3% of silicon, up to 1% of niobium, up to 5% of tungsten and in each case up to 0.5% of hafnium, titanium, rare earths, zirconium, and up to 6% of aluminum.
32. The use as claimed in claim 31, in which the alloy contains, individually or in combination with one another, at least 0.02% of silicon, 0.1% of niobium, 0.3% of tungsten and 1.5% of aluminum.