VIBRATIONS OF TUBES IN HEAT EXCHANGERS

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begell house, inc
New York • Wallingford (UK)

This book was translated by Irina Rybakova.

Library of Congress Cataloging-in-Publication Data

Katinas, Vladislavas.
Vibrations of tubes in heat exchangers / Vladislavas Katinas, Algirdas Zukauskas.
p. cm.
Includes bibliographical references and index..
ISBN 1-56700-077-0
1. Heat exchangers--Vibration. I. Zhukauskas, A. A. (Al'girdas Alfonsovich), 1923- . II. Title.
TJ263.K33 1997
621.402'5--dc21 96-45098
CIP

Contents

Preface

The current volume of the "Thermal Physics" series is concerned with tube vibrations in heat exchangers. Causes of the vibrations are ascertained. Possibilities of allowing for them are considered, and scientifically grounded recommendations for suppressing them to an admissible level are given. A large body of information on studying unsteady hydrodynamic processes and forces acting on the elements of structures in a flow is presented.

The first unified data on the flow-induced tube vibrations were reported in the monographs "Convective Transfer in Heat Exchangers" (1982) by A. Žukauskas and "Fluid Dynamics and Vibrations of Tube Bundles in Flow" (1984) by A. Žukauskas, R. Ulinskas and V. Katinas. The reviews of these publications indicated that the presented data on the flow-induced tube vibrations enjoy a wide application and are of interest for many designers of heat exchangers, as well as for researchers dealing with the problems of fluid dynamics and heat transfer in industrial power plants.

In recent years the Institute has accumulated new extensive data on the flow-induced tube vibrations that were published in various literature sources. Therefove, we set out to revise the available material, complete it with the latest data and document in the plan of scientific advances. Similarity correlations for predicting stability of tube arrays in the flows of heat-transfer agents were derived and reported.

The first chapter of the book treats structural features of the tube arrays of heat-transfer constructions of the heat exchangers, gives a general information on the fluid dynamics and flow-induced tube vibrations and techniques of taking into account the intensity of tube vibrations proceeding from the material strength.

The second chapter describes experimental facilities, operation principles of the measuring elements and investigation methods.

The third chapter is devoted to data on the unsteady fluid-dynamic processes occurring in a detached flow past the tubes and on fluid-dynamic forces acting on the tubes.

The fourth, fifth and sixth chapters provide theoretical results and experimental data for the flow-induced vibrations in various tube arrays, viz bundles of parallel tubes in a cross flow, radial tubes, inclined tubes, tube bundles turned relative to the flow direction, and also on individual tubes and in their systems. The studies employed smooth, finned as well as uniformly and nonuniformly placed circular and plane-oval tubes. Measures for averting the flow-induced tube vibrations were explored.

The seventh chapter covers a technique of predicting the flow-induced tube vibrations and methods of suppressing an acoustic resonance originating in heat exchangers. Indications are given on the selection of the range of operating velocities of the heat-transfer agent with consideration of stability of the heat-transfer constructions in its flows.

The book has come to light owing to the financial support of the Lithuanian State Department of Science, Engineering and Technologies.

The authors wish to express their gratitude to scientific workers E. Perednis, A. Marcevičius, A. Tumosa, V. Šuksteris, R. Bakas et al., who participated in the experimental studies and data processing, and also to J. Žiugžda, L. Burkoj and to all those, who assisted in preparing the book manuscript for publication.

Nomenclature

$\bar{A}$, $\bar{A}_x$, $\bar{A}_y$ - rms amplitudes of tube vibrations in any, longitudinal and transverse directions relative to the direction of an incident flow, m;

a - relative transverse pitch (s_1/d), thermal diffusivity, m^2/s;

b - relative longitudinal pitch (s_2/d);

b' - relative diagonal pitch of the staggered bundle (s'_2/d);

c_D - total drag $(P_D/(0.5dl\rho\bar{u}^2))$;

s_f - friction drag $(P_f/(0.5dl\rho\bar{u}^2))$;

c_w - pressure drag $(P_w/(0.5dl\rho\bar{u}^2))$;

c_x, c_y - coefficients of the longitudinal and transverse nonstationary fluid-dynamic forces $(P_x/(0.5dl\rho\bar{u}_2))$, $(P_y/(0.5dl\rho\bar{u}^2))$;

d - diameter, m;

e - nondimensional displacement of the tubes relative to the symmetric position ($y/(s_1-d)$);

$\bar{e}$ - relative spacing between the tube bundle and the wall ($h/(s_1-d)$);

l - tube length, m;

l_c - correlation length, m;

Δl - distance between two measurement points, m;

F - force, N;

f - frequency, Hz;

f_s - frequency of vortex shedding, Hz;

f_n - natural frequency of tube vibrations, Hz;

h	- channel height; minimal flow section between the end tube of the bundle and the channel wall, m;
m	- design mass of the tube per unit length ($m_t + m_a + m_l$), kg/m;
m_t, m_a, m_l	- tube mass, additional fluid mass and fluid mass in the tube, respectively, kg/m;
P_D	- resultant drag force ($P_f + P_w$), N;
P_f, P_w	- resultant of the frictional forces and resultant of the pressure forces, respectively, N;
P_x, P_y	- longitudinal and transverse stationary fluid-dynamic forces, N;
p	- pressure, Pa;
Δp	- pressure drop, Pa;
$\bar{p}$	- pressure coefficient $(1 - \Delta p / (0.5 \rho \bar{u}^2))$;
S_A, S_u	- spectral density of the tube vibration amplitude and of the flow velocity fluctuations, respectively, s;
s_1, s_2	- transverse and longitudinal pitches between the bundle tubes, m;
s_2'	- diagonal pitch of the staggered tube bundle, m;
Tu	- turbulence degree, $\sqrt{\overline{u'^2}}/\bar{u}$
t	- time, s;
Δt	- time interval, s;
U_0	- velocity of the incident flow, m/s;
$\bar{u}$	- velocity in the narrow cross section of the bundle ($U_0 a/(a-1)$), m/s;
u, v, w	- components of the flow velocity, m/s;
u', v', w'	- fluctuating components of the flow velocity, m/s;
X, Y	- drag and lift forces, respectively, N;
x, y, z	- Cartesian coordinates, m;
α	- angle of the bundle turn relative to the flow direction, deg.; thermal conductivity, W/(m^2K);
β	- angle of the tube inclination to the flow direction, deg.;
δ	- logarithmic decrement;
μ	- dynamic viscosity, Pa·s;
γ	- kinematic viscosity m^2/s;
ρ	- fluid density, kg/m^3;
σ	- stress, N/m^2;
φ	- angle, deg.;
ω	- angular frequency ($2\pi f$), 1/s;
Pr	- Prandtl number (ν/a);

Re - Reynolds number ($\bar{u}d/\gamma$);

Sh - Strouhal number ($f_s d/\bar{u}$);

Sh_n - nondimensional vibration frequency of the tubes ($fd/\bar{u}$).

Subscripts:

f, 0 - in the undisturbed flow;
w - at the wall;
$(\bar{\ })$ - averaging;
$(\ )'$ - fluctuating components.

The remaining nomenclature is given in the text.

1

Introduction

1.1 General Information

The development of power engineering, chemical and oil-refining industries, vehicle construction and other areas of engineering is characterized by a significant enhancement of the processes of heat and mass transfer, by a reduction of the specific amount of metal and by an increase in the energy stress of heat exchangers. These areas [1] widely apply tube recuperative heat exchangers (Fig.1.1) in which both heat-transfer agents (working fluids) simultaneously flow over a heat-transfer surface and the heat is transferred from the primary to the secondary heat-transfer agent through a wall dividing them. Such a way of heat transfer allows the creation of a heat exchanger that meets all imposed requirements. The structures of heat exchangers are diverse and predominated by parameters of the working fluids.

Much used in practice are shell-and-tube heat exchangers (Fig. 1.2) assembled from different-curvature tubes, *viz.* straight, U-shaped, coil, helical and others. A tube surface can be smooth, finned and other, whereas a cross section can be circular, plane-oval, elliptical, etc. A spatial orientation of the heat-transfer surface in the apparatus (Figs. 1.1 and 1.2) can be vertical, horizontal and inclined.

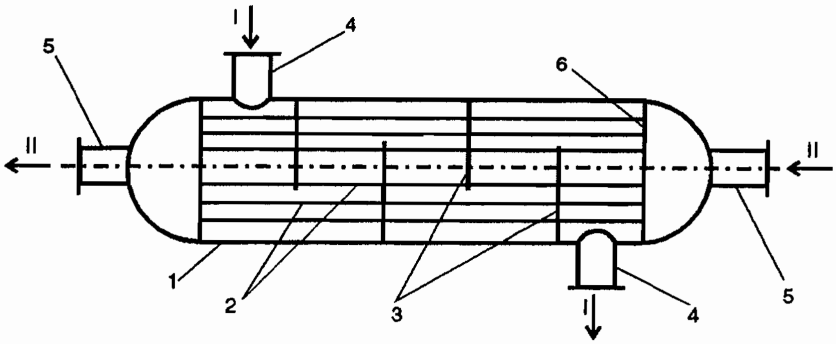

Fig. 1.1 Schematic of a recuperative heat exchanger: 1 – frame; 2 – heat-transfer surface; 3 – partitions (spacing grids); 4, 5 – inlets and outlets of the primary (I) and the secondary (II) heat-transfer agents; 6 - tube grid (board).

A great problem is presented by a thermal extension of the recuperative heat exchangers. Rigid-structure heat exchangers and those with the extension compensation by elastic elements are manufactured. First, (Fig. 1.2 a) straight heat-transfer tubes in the shell are connected rigidly to tube grids and second, the tubes and the shell can shift relative to each other. In these cases, U-shaped tubes (Fig. 1.2 b), moving floating tube grids and curved tube sections (Fig. 1.2 c, d), compensating for the thermal extension, are frequently applied. The thermal

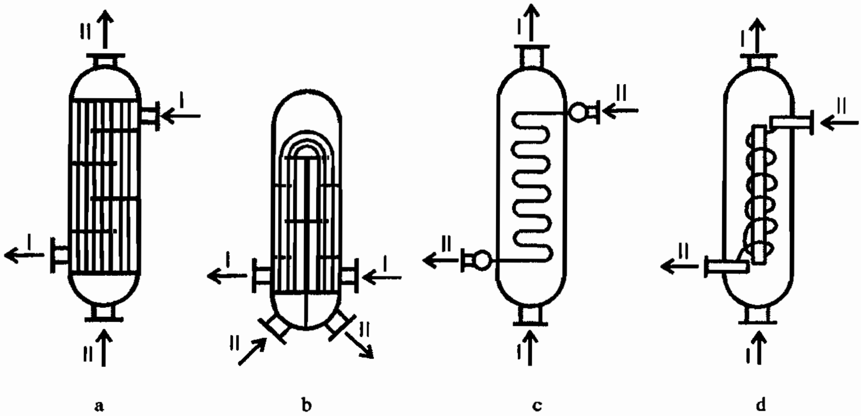

Fig. 1.2 Schematic diagrams of tube arrangements in the shell-and-tube heat exchangers with straight (a), U-shaped (b), coil (c) and helical (d) tubes.

stresses change vibromechanical characteristics of the heat-transfer tubes. Therefore, the questions of thermal deformations have to be solved at the stage of designing heat exchangers.

Circulation of the heat-transfer agent in the heat exchanger can be natural, forced or due to gravity. The heat exchanger shell can be box-like, tubular or of a different shape.

Depending on the designated purpose, various processes occur in heat exchangers, *viz.* heating, cooling, boiling, condensation, freezing-out, rectification, etc. Therefore, heat exchangers are subdivided into heaters, coolers, evaporators, steam generators, condensers, etc.

As the heat-transfer agents, use is often made of liquids, *viz.* water, various oils, liquid metals (sodium), organic substances (glycerin and others) or of gases, *viz.* air, hydrogen, helium, carbon dioxide and others. With rising temperature, liquid heat-transfer agents change to gaseous, and the higher is a pressure of the working fluid, the higher are temperatures at which this change occurs. At high pressures gaseous heat-transfer agents can transform into liquid.

In identical conditions and modes of the flow past tubes (Fig. 1.3) which are

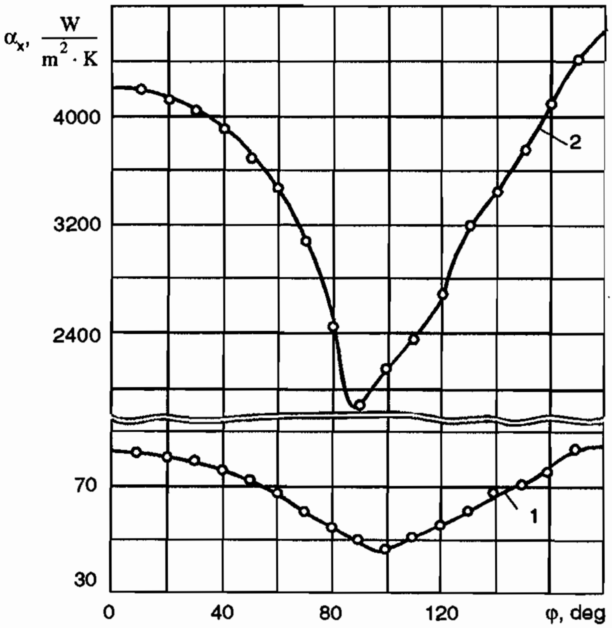

Fig. 1.3 Variation in the heat transfer coefficient round the perimeter of a circular tube at **Re** $\cong 5 \cdot 10^4$ in air (1) and water (2) flows.

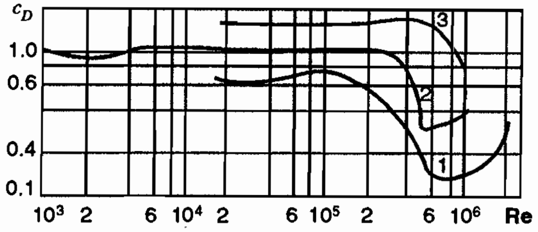

Fig. 1.4 Variation in the drag of the tubes of circular and elliptic cross sections: 1 – with a flow past a major axis of the elliptical tube with an axes ratio of 1:2; 2 – with a flow past the circular tube; 3 – with a flow past a minor axis of the same elliptical tube.

characterized by a Reynolds number, the beat-transfer coefficient [2] in a water flow is generally by one or two orders of magnitude greater than that in an air flow. However, the better is streamlining of the tubes and the lower is the drag (Fig. 1.4), the worse is the heat transfer (Fig. 1.5).

Various circulation schemes of the working fluids are employed in designing heat exchangers, *viz.* gas-gas, liquid-liquid, gas-liquid, steam-steam, steam-gas and steam-liquid schemes. With operation by the first scheme, the beat transfer coefficient of gas [2] is not high (Fig. 1.3), therefore, the overall dimensions of heat exchangers are large. With operation by the second scheme, the specific amount of metal of the heat exchanger decreases appreciably. In the case of the

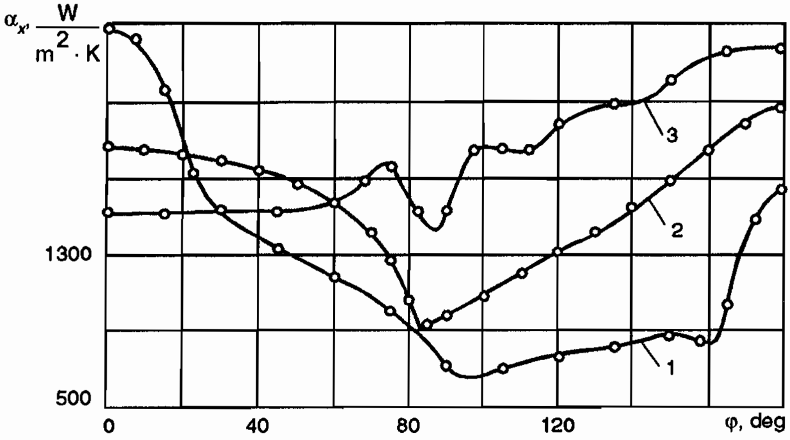

Fig. 1.5 Variation in the heat transfer coefficient round the perimeter of the tubes of elliptical and circular cross sections at **Re** $\cong 2 \cdot 10^4$ in the flow of transformer oil (see designation 1–3 in Fig. 1.4).

third operational scheme, it should be borne in mind that the heat transfer coefficient of gas is markedly smaller than that of liquid. To attain equal heat transfer from both sides of the tubes, finned tubes [3] that allow about a 20-fold enlargement of the area of heat transfer from gas are much used instead of smooth. With the steam-liquid scheme, smooth tubes are applied because a great heat quantity is removed in the steam condensation. Many problems associated with heating, cooling and condensation of the working fluids are solved using developed heat-transfer surfaces. Having balanced the heat-transfer coefficient it is possible to reduce the specific amount of metal, overall dimensions and cost of the heat exchanger.

Reliability and durability of the heat exchanger are largely governed by the intensity of the vibrations of heat-transfer elements induced by the flows of heat-transfer agents. Particular requirements of stability of the heat-transfer tubes in the flows of heat-transfer agents are specified for heat exchangers utilized in nuclear engineering and in other special cases, when every possibility of the working fluid flow from one loop to another is ruled out, since this may cause emergency in the reactor. Therefore, in designing the state-of-the-art heat exchange equipment a complex problem needs to be solved that encompasses the questions of heat transfer, fluid dynamics and stability of tubes in the flows of heat-transfer agents, as well as of heat transfer enhancement.

Methods for enhancing a convective heat transfer [4–9], which determine an energy efficiency of the heat exchangers, can be separated into passive, active and complex.

Among passive methods is the use of finning of the tubes and of other developed surfaces from the side of the heat-transfer agent with a low heat- transfer coefficient, of agitating networks, swirlers, rough surfaces and also of facilities that break down the boundary layer and increase the heat transfer.

Active methods necessitate the use of an extra external energy, e.g. of ultrasound, tube vibrations, rotation of the heat-transfer surfaces, electric field, etc.

Complex methods are those with which not more than two types of enhancement of the convective heat transfer are applied simultaneously. A case in point may be the heat-transfer surfaces fabricated from finned tubes with insertions for flow swirling. Here the convective heat transfer from the inner and the outer sides of the heat-transfer element is enhanced.

It should be remembered that the heat transfer enhancement entails an increase in the energy consumption on pumping of the heat-transfer agent and a change of the fluid dynamic forces acting on the tubes. Heat transfer, fluid dynamics as well as strength and stability of the tubes in the flows of heat-transfer agents are predicted with consideration of this fact. The tube stability is specified by a level of the vibrations of heat-transfer structures excited by the flows of heat-transfer agents past them. Up till recently little attention has been afforded to the flow-induced tube vibrations, however, in updating the heat exchangers this problem has become one of the primary for carrying out thermohydraulic predictions.

Studying the vibrations of heat-transfer elements in the flows of heat-transfer agents involves the investigation of steady and unsteady fluid dynamic processes brought about by the streamline flow. The flow past tubes can be longitudinal, cross and oblique. In the first case, the tubes are streamlined without a fluid separation from their surface and in the second, with a fluid separation. The fluid flow near the tube surface is characterized by instantaneous fluid-dynamic processes of local and integral effect. The flow-induced vibrations are determined by a character of the flow past tubes, by an interaction with the streamlined structure, by a fluid flow through the tube arrays, by an additional fluid mass, by parameters of the incident fluid and by surface characteristics of the heat-transfer tubes.

Two basic problems are differentiated in the investigations of the vibrations of heat-transfer elements, one of them related to the flow past tubes and the other to their vibrations. The flow-induced tube vibrations are determined by a vortex shedding from the tubes, turbulence of the incident flow, nonstationary forces acting on the tubes, etc. The consideration of the vibrations of flow-excited tubes involves the identification of excitation types, of statistical characteristics, of an interaction between the vibrations of individual tubes of a bundle, of a vibration effect on the streamline flov and of many other factors. Such a comprehensive investigation makes it possible to ascertain an actual pattern and causes of the vibrations of tube systems in the flows of heat-transfer agents and to find scientifically justified control measures.

Obtaining optimal technical and economic characteristics of the heat exchangers requires a correct choice of their structural model, materials, dimensions of the elements of the surface heat transfer, as well as of the type and velocities of the working fluids. The structural models of heat exchangers should be selected proceeding from minimal capital outlays and service costs.

The book presents results of the experimental and theoretical study of unsteady fluid dynamic processes and forces acting on the tubes in a detached flow and of flow-induced tube vibrations. Consideration is given to the arrays of tubes of circular and plane-oval cross sections. Based on the investigations conducted in the Institute for Physical and Technical Problems of Power Engineering (at present the Lithuanian Energy Institute) the data, acquired in scientific centers of other countries over the past 20 years, are generalized. A good deal of attention is given to elucidating a physical essence of the origination of the vibrations of beat-transfer elements excited by the flows of gas and liquid heat-transfer agents. Mathematical models and methods for predicting the vibration parameters of tube and rod arrays, employed in heat exchangers, are refined. The regularities of the flow action on heat-transfer elements and the unsteady fluid-dynamic processes occurring in the detached flow past tubes are treated. The problems of a flow past tubes and of flow-induced tube vibrations, as well as the interrelationships among the tube parameters and vibrations and the flow past tubes are considered in detail in studies [10, 11]. Recently the above-stated Institute has conducted additional investigations and obtained new data of theoretical and applied significance. The current study unified this material and put forward scientific and practical indications on preventing hazardous vibrations of the tube systems of heat exchangers.

The study of the probem of vibrations of the heat exchanger heat-transfer elements in a flow includes three stages:

– a discussion and a qualitative description of the processes of fluid dynamics and tube vibrations induced by the flow;

– a construction or a refinement of the mathematical description of these processes which contains a number of experimental coefficients or constants; and

– a determination of the values of the above coefficients or constants characterizing a force action of the flow on the tubes and vibration parameters of the heat exchanger structures in a flow.

The third stage requires a perfomance of numerous experiments covering the entire range of geometric characteristics of the tube arrays of heat exchangers as well as of conditions of the gas and liquid flows past them. In assessing the conditions of instability arising from the flow-induced tube vibrations it is necesary to carefully take into account variations in the conditions of the flow past tubes on models and in in-frame structures of the heat exchangers. Any changes in the conditions of the flow past tubes markedly alter their vibration characteristics. All these aspects are considered using the models of tube arrays under various conditions of the flow past tubes. Theoretical evaluations of the hydrodynamically induced vibrations caused by fluid dynamic forces from the side of flow are developed based on differential equations for rod vibrations with a view to the type of the tube excitation by the flow and on a mathematical description of the flow action on the tubes. Predictions are compared with measurement results for vibration parameters of the tube of real heat exchangers or of the models of their elements. Plausibility of the obtained data and correction factors for the predictions are determined. Rules and analytic relations for selecting the ranges of operating velocities of the heat-transfer agents with allowance for the tube vibrostability are presented.

1.2 In-Frame Arrangement of Tube Heat Exchangers

To improve the heat-transfer efficiency in shell-and-tube heat exchangers various structural elements are employed that ensure a high-rate heat exchange by vortex structures between the boundary layers and the flow core both in tubular and intertubolar spaces.

The main heat-transfer elements of the heat-transfer surfaces (Fig. 1.1) are

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