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Introduction and Typical Vibration Problems

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1.1 Introduction

Excessive flow-induced vibration must be avoided in process and nuclear system components. That is the purpose of this handbook. The term "process components" is used generally here to describe nuclear reactor internals, nuclear fuels, piping systems, and all shell-and-tube heat exchangers, including nuclear steam generators, power plant condensers, boilers, coolers, etc. Higher heat-transfer performance often requires higher flow velocities and more structural supports. On the other hand, additional supports may increase pressure drop and costs. The combination of high flow velocities and inadequate structural support may lead to excessive tube vibration. This vibration can cause failures by fatigue or fretting wear. Failures are very undesirable in terms of repair costs and lost production, particularly for high-capital-cost plants such as nuclear power stations, petroleum refineries and oil exploitation platforms. To prevent these problems at the design stage, a thorough flow-induced vibration analysis is recommended. Such analysis requires good understanding of the dynamic parameters and vibration excitation mechanisms that govern flow-induced vibration.

This handbook covers all relevant aspects of component vibration technology, namely: examples of vibration failures, flow analysis, and vibration excitation and damping mechanisms. The latter includes fluidelastic instability, periodic wake shedding, acoustic resonance, random turbulence, flow-induced vibration analysis and fretting-wear predictions.

Chapter 2 is an overview of flow-induced vibration technology. The reader should start with this chapter. In many cases, Chapter 2 will be sufficient to provide the required information. Each aspect of the technology is covered in detail in the succeeding chapters. Typically, each chapter includes a review of the state of the art, available laboratory data, brief review of theoretical considerations and modeling, parametric analysis, recommendations for design, and sample calculations.

The performance of process components is often limited by excessive vibration in a localized area, e.g., near inlets, outlets, etc. The combination of detailed flow calculations and vibration technology allows the designer to avoid such problems. Flow velocities and support design can be optimized to allow maximum heat transfer in all regions of process components, resulting in higher heat-transfer performance, less corrosion and fouling problems and reduced component size. The latter means capital cost reduction and a more competitive manufacturing industry.

This handbook is for the practicing engineer who is designing or troubleshooting nuclear and process system components. Design guidelines are proposed based on extensive analysis of the

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literature and, in particular, on experimental data obtained in the field and at the Canadian Nuclear Laboratories of Atomic Energy of Canada Limited at Chalk River, Ontario, Canada. Although it is not intended as an undergraduate text book, it could be useful as a source of design data and practical examples. To assist students and new design engineers, the example calculations provided throughout this handbook are supplemented and presented with more explanation in Appendix A.

There are already several useful books on flow-induced vibration, e.g. Au-Yang (2001), Blevins (1990), Chen (1987), Kaneko et al (2014), Naudascher and Rockwell (1994), and Païdoussis (1998). So, why another one in the form of a handbook? This book is complementary to the above books for the following reasons. This book has greater emphasis on design guidelines. Much experimental data is presented in the form of comprehensive data bases that include a significant number of two-phase flow results. Particular attention is given to damping in single- and two-phase flow, two-phase flow-induced vibration mechanisms such as fluidelastic instability and random turbulence excitation, and the prediction of fretting-wear damage. Simple examples of calculations are given throughout the handbook.

1.2 Some Typical Component Failures

In heat exchangers, tube failures due to fretting wear may occur at the tube supports or at midspan if the tubes vibrate with sufficient amplitude to contact each other. Figure 1-1 shows an example of tube-to-tube fretting wear. It occurred in the U-bend of an early nuclear steam generator with tubes that were inadequately supported near the outlet in a region of high-velocity two-phase cross flow. Extensive fretting-wear damage was also observed between tube and tube support, as shown in Fig. 1-2. Here, the damage was sufficient to cause a hole in the tube resulting in leakage between tube-side and shell-side. Obviously, this kind of problem must be avoided. An additional support near the outlet region was an easy solution to this problem.

Figure 1-3 shows extensive tube-to-tube fretting-wear damage in the inlet region of a triple segmental liquid-liquid process heat exchanger. The problem was due to the combination of long tube spans (1.45 m) and high flow velocities impinging directly on the tubes in the inlet region. Lacing

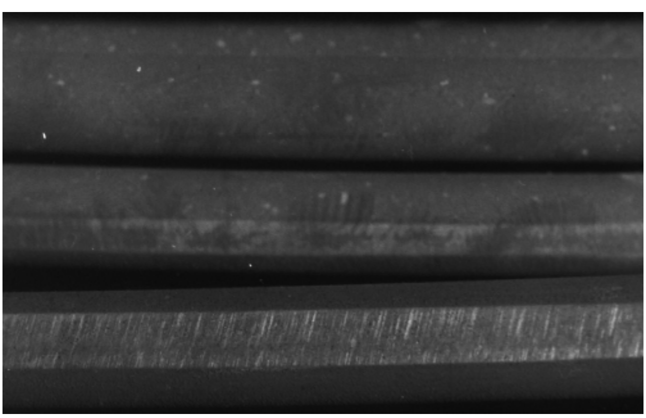

Fig. 1-1 Tube-to-Tube Fretting Wear in the U-Bend Region of an Early Nuclear Steam Generator (Pettigrew, 1976).

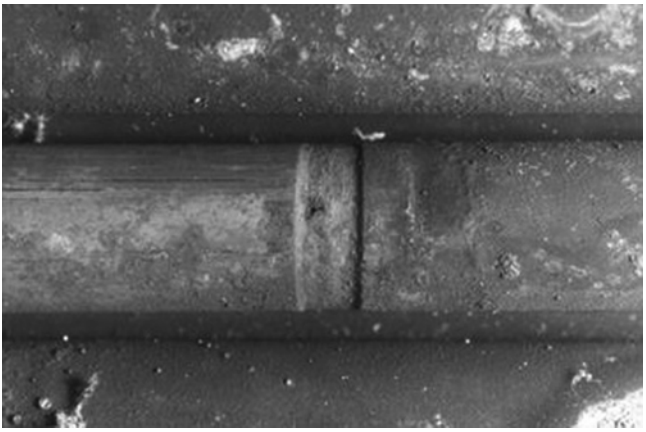

Fig. 1-2 Tube-to-Support Fretting Wear: Note Hole Through Tube Wall (Pettigrew, 1976).

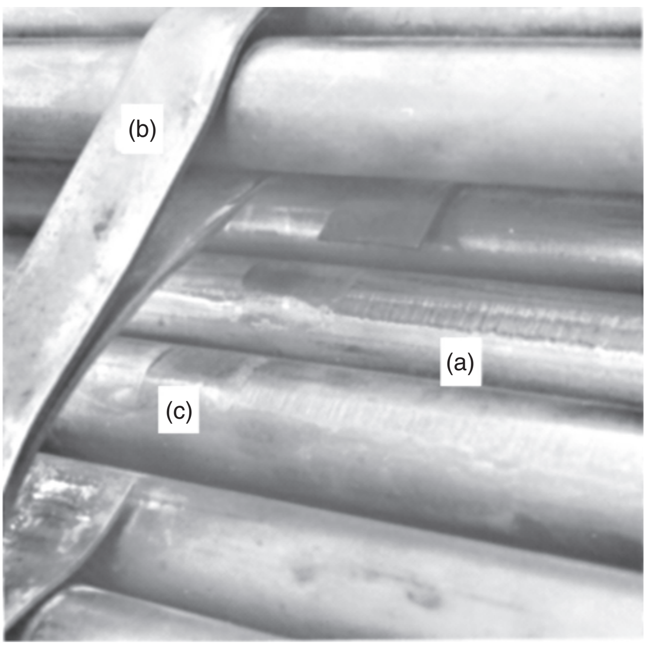

Fig. 1-3 Fretting Wear in the Inlet Region of a Liquid Process Heat Exchanger: a) Tube-to-Tube Initial Damage, b) Lacing Strip, and c) Damage at Lacing Strip Location (Pettigrew, 1976).

strips were installed to support the tubes near the inlet. Unfortunately, they were excessively loose. Fretting wear occurred between the tube and the lacing strips. Tubes wore through, as shown in Fig. 1-4. Eventually, proper baffle-supports were installed, as shown in Fig. 1-5. No further problems occurred.

In power condensers, very-high-velocity steam may impinge on the tubes, causing excessive vibration. Figure 1-6 shows a fatigue failure of a titanium condenser tube. The vibration amplitude was

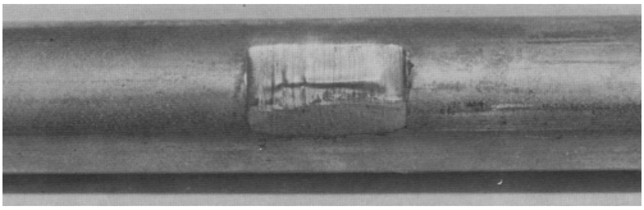

Fig. 1-4 Fretting Wear Through Tube Wall at a Lacing Strip Location in a Process Heat Exchanger (Pettigrew et al, 1977).

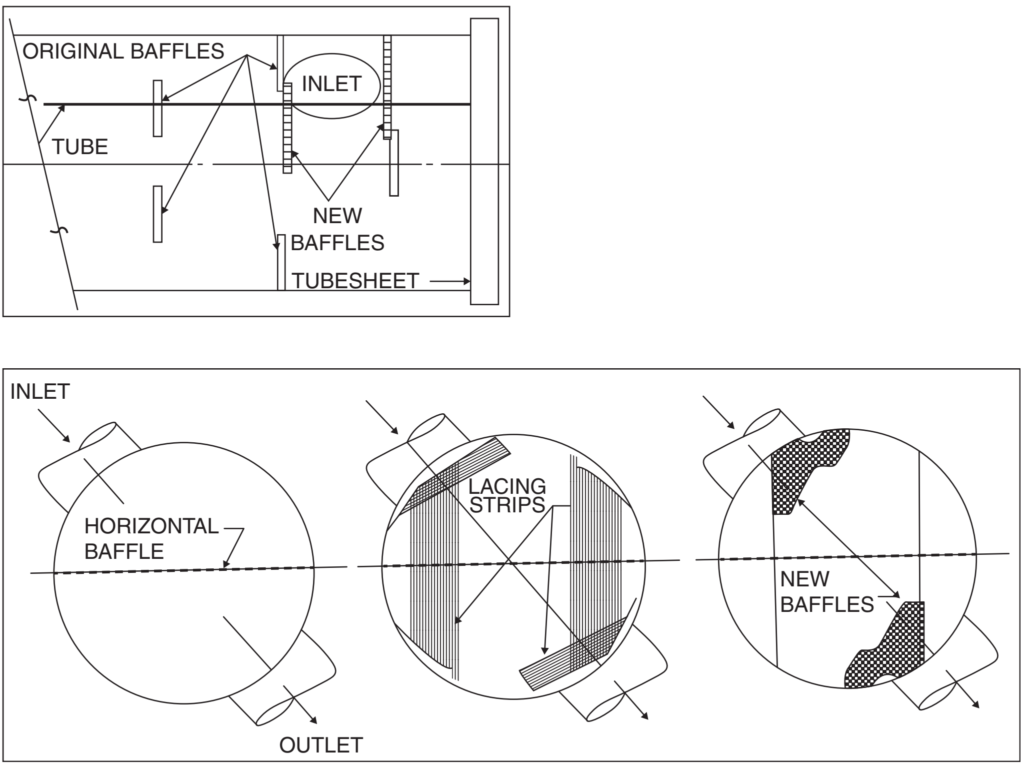

Fig. 1-5 Fretting Wear of Process Heat Exchanger: Repair (Pettigrew and Campagna, 1979 / with permission of Atomic Energy of Canada Limited).

sufficient for the tubes to contact each other at midspan. In this case, the condenser was operated with only four of the six tube bundles, resulting in 150% of design flow velocity. Operation at 100% design flow did not cause any vibration damage.

Figure 1-7 shows tube-to-tube fretting-wear damage in another power condenser. In this case, the damage was sufficient to wear through the tube wall, causing leakage of sea water into the secondary side of a power plant.

An example of fretting-wear damage of a tube located just beyond the baffle cut (window tube) vibrating against a baffle edge is shown in Fig. 1-8. This tube came from a gas-to-gas heat exchanger,

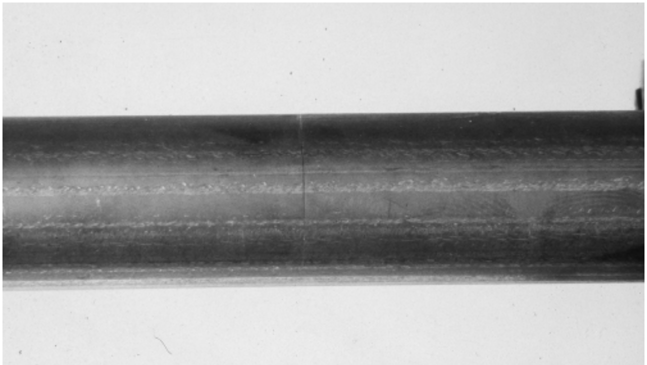

Fig. 1-6 Fatigue Failure of a Titanium Tube in a Nuclear Power Plant Condenser (Pettigrew et al, 1991).

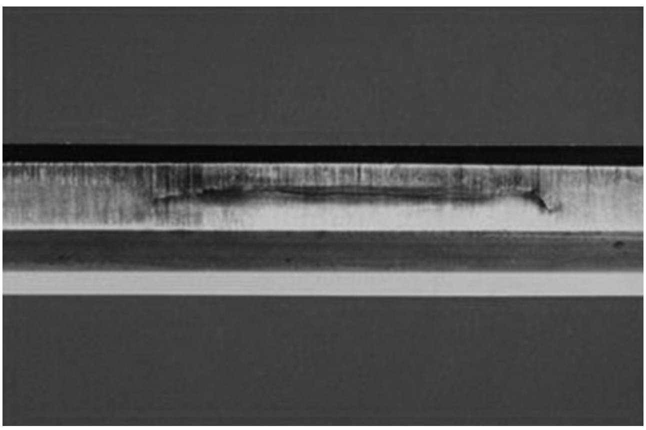

Fig. 1-7 Tube-to-Tube Fretting Wear in a Power Plant Condenser.

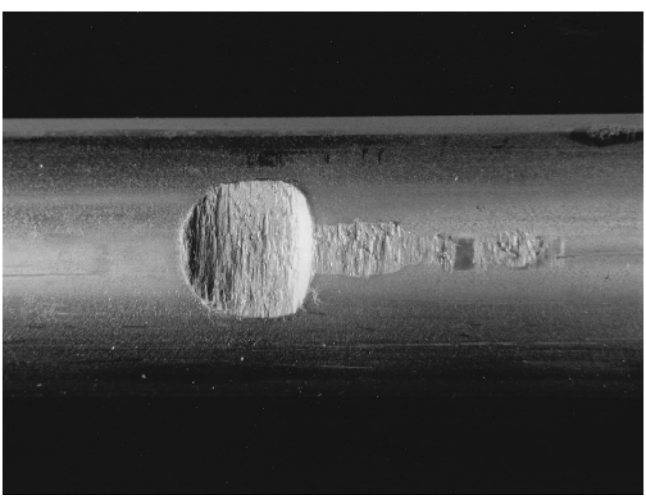

Fig. 1-8 Fretting Wear of a Gas Heat Exchanger Tube at a Baffle Edge Location.

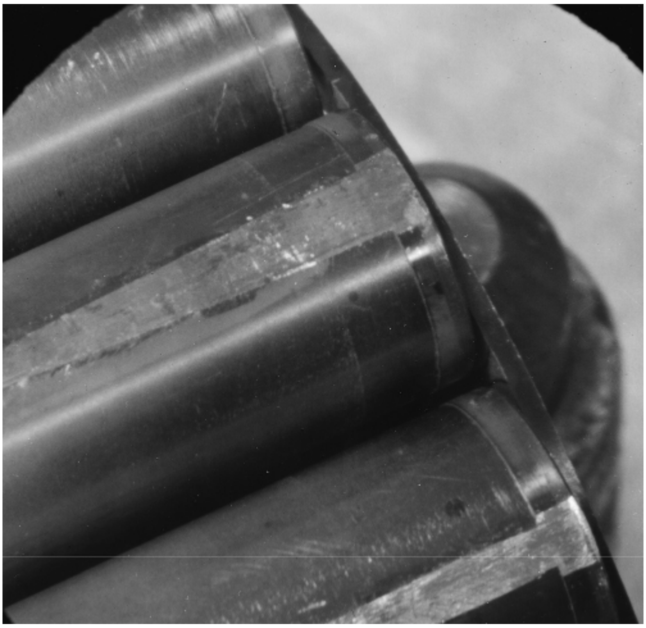

Fig. 1-9 Fretting-Wear Damage on Nuclear Fuel (Hot Cell Examination) (Pettigrew, 1976).

which was inadvertently operated at several times above design flow during a commissioning operation.

Figure 1-9 is an example of fretting wear of nuclear fuel as seen through an optical magnifier during "hot cell" examination. The damage occurred at the top of fuel string assemblies in 40% of the high flow fuel channels of a prototype CANDU-BLW®[1] nuclear station. The fuel strings were inserted in upward-flow vertical fuel channels where they were attached at the bottom and free at the top. The flow in each channel became two-phase as boiling occurred along the fuel and reached approximately 16% steam quality near the top. The mass flux was typically 4400 kg/m^2 s. The fretting problem was attributed to transverse flow-induced vibration of the fuel strings. Inadvertently, some of the fuel strings were assembled eccentrically. This caused the strings to be bent and promoted fretting wear. The corrective measures taken were to ensure concentric assembly of the fuel and increase fuel string flexural rigidity to reduce vibration.

One of the most costly vibration related problems took place in the early 1990s at the Darlington Nuclear Power Station, where nuclear fuel bundles were seriously damaged by fatigue and fretting wear (Fig. 1-10). The cost of investigation, repairs and particularly lost production totalled approximately 1 billion dollars Canadian. The problem was caused by acoustic resonance in the inlet headers due to coincidence of the pump pressure pulsation frequency, (30 Hz x 5 vanes = 150 Hz) and the natural acoustic frequency of the headers. The pressure pulsations were transmitted and amplified in the fuel channels, subjecting the fuel bundles to significant pressure fluctuations causing extensive damage. The problem was solved by simply replacing the five-vane pump impellers by seven-vane impellers, thus eliminating the acoustic resonance.

Sometimes vibration problems develop because of changes in operating conditions. For example, pressurized water reactor (PWR) fuel failures occurred in the 1990s due to fretting wear between fuel rods and support grids. The problem was related to longer fuel residence time, which caused increased clearances between the rods and grids due to creep, and deregulation of fuel

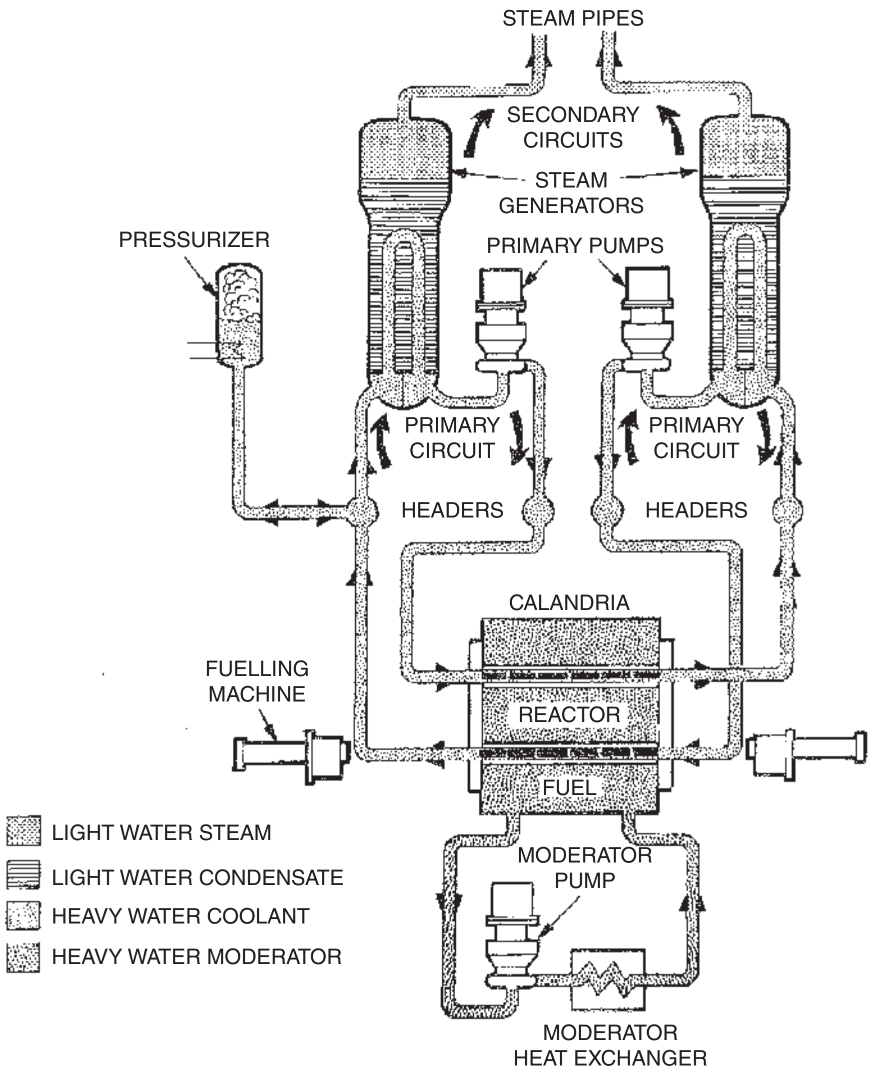

Fig. 1-10 Schematic Drawing of CANDU-PHW®[2] Reactor (Pettigrew, 1978 / with permission of Atomic Energy of Canada Limited)

procurement. The latter allowed fuels from different suppliers at the same time in the reactor core. Differences in design caused slight differences in impedance resulting in increased cross flows and, thus, more flow-induced vibration excitation. Changes in support grid design solved this problem.

Vibration problems are not limited to material damage such as fatigue and fretting wear. For example, excessive vibration of control absorber guide tubes due to jet impingement could have caused a serious reactor control problem (see Fig. 1-11a). The problem was avoided by shielding the guide tube with a protective shroud, as shown in Fig. 1-11b.

Many other vibration problems have been encountered, such as fatigue failures of PWR core barrel tie rods and in-core instrumentation nozzles, excessive acoustic noise due to control valve

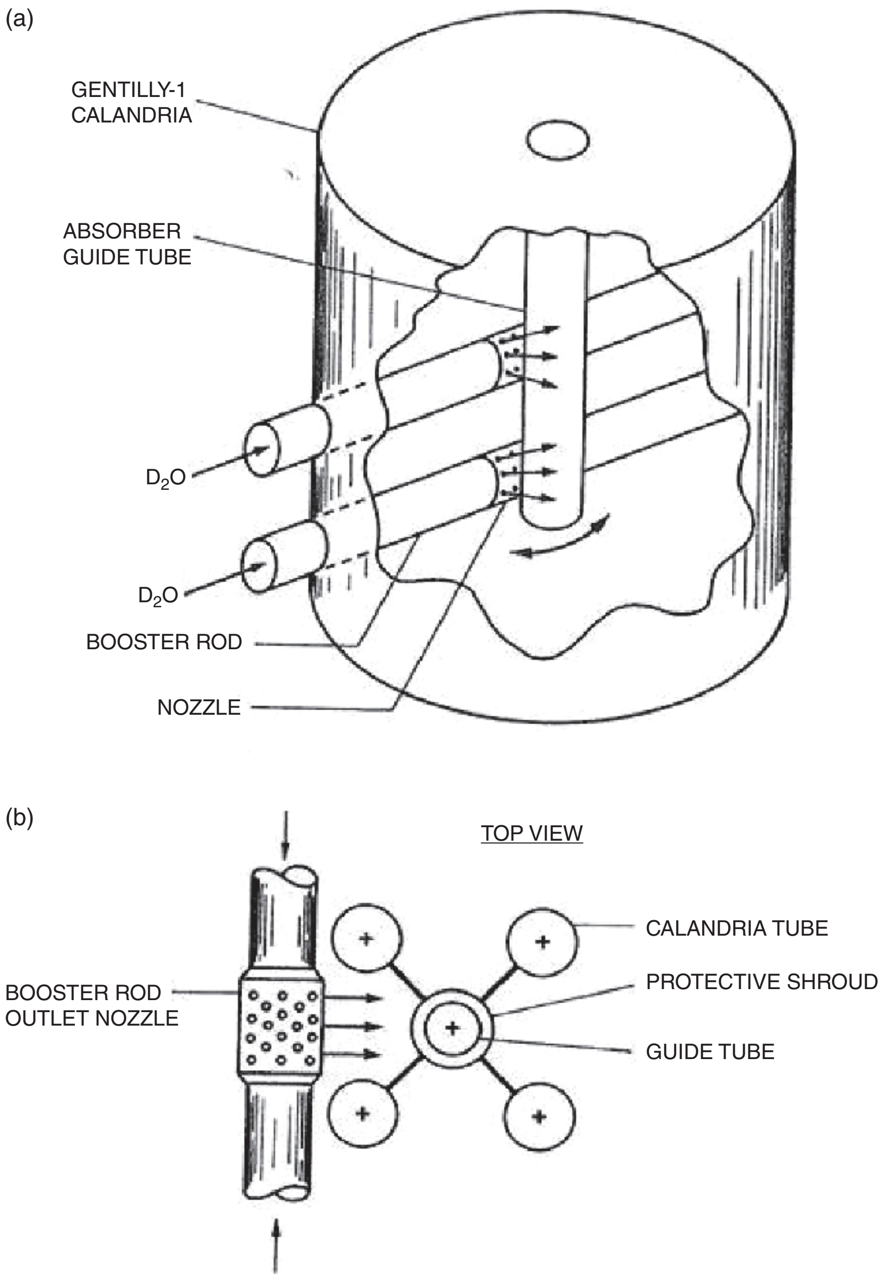

Fig. 1-11 a) Control Absorber Guide Tube Vibration due to Jetting, b) Modification with Protective Shroud (Pettigrew, 1976 / with permission of Atomic Energy of Canada Limited).

dynamics and mechanical damage resulting from acoustic resonance in gas heat exchangers. Although most vibration problems have very costly consequences, they are usually solved by simple design modifications or changes in operating conditions. After the fact, it is easy to see that most problems could have been avoided by proper understanding of flow-induced vibration phenomena.

Thus, it is important to understand flow-induced vibration and damage mechanisms to prevent problems at the design stage and assist plant operators in predicting the life of components. It is hoped that this handbook will help in that direction.

1.3 Dynamics of Process System Components

1.3.1 Multi-Span Heat Exchanger Tubes

From a mechanical dynamics point of view, heat exchanger and steam generator tubes are multi-span beams clamped at the tubesheet and held at the baffle supports with varying degree of constraint (see Fig. 1-12). The degree of constraint depends on support geometry and, particularly, on tube-to-support clearance. Heat exchanger dynamics is inherently a non-linear phenomenon since it depends largely on the interaction (impacting and sliding) between a particular tube and its supports. This non-linearity is particularly important since it governs the evaluation of damping at the supports and the prediction of fretting-wear damage to the tube.

Such analysis requires time domain non-linear simulation of the tube dynamics in which the details of sliding-friction, impact, viscous-shear and squeeze-film forces between tube and tube supports are modelled. Unfortunately, non-linear simulations are difficult and some of the detailed information is lacking. Furthermore, the required non-linear analysis is not yet in the form of a practical design tool. Some progress has been made in this area with the development of codes, such as VIBIC (Fisher et al, 1992), H3DMAP (Sauvé et al, 1987) and EPRI SG FW (Rao et al, 1988) to predict fretting wear of heat exchanger tubes.

In the future, we believe that all vibration analyses will consider non-linear simulation of the dynamic interaction between tubes and supports and will include a fretting-wear damage prediction. This kind of analysis is now done by specialists for very critical or very expensive components, such as nuclear steam generators. Fretting-wear damage prediction is discussed in Chapter 12.

For the time being, quasi-linear vibration analyses are used by the industry for most heat exchangers. Quasi-linear analysis requires the formulation of tube-to-support dynamic interaction forces, such as damping, in terms of equivalent linear values. We have found this approach to be reasonable in practice for the prediction of overall tube vibration response and critical velocities for fluidelastic instability. Such analysis is adequate to eliminate most vibration problems. However, long-term fretting-wear damage and tube life can only be predicted in an approximate manner. Tube vibration measurements in real heat exchangers show generally good agreement between measured and predicted frequencies using the quasi-linear approach.

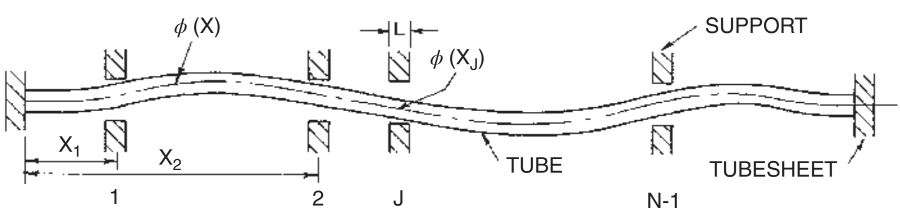

Fig. 1-12 Multi-Span Heat Exchanger Tube with N Spans and N-1 Clearance Supports.

1.3.2 Other Nuclear and Process Components

Other process and nuclear system components, such as nuclear fuels, reactor internals, and piping systems, are often multi-span beams with intermediate clearance-type supports (e.g., piping supports, fuel bearing pads and support grids). Analysis of these components is similar to that of multi-span heat exchanger tubes.

Notes

1 CANDU-BLW = Canada Deuterium Uranium – Boiling Light-Water is a registered trademark of Atomic Energy of Canada Limited.
2 CANDU-PHW = Canada Deuterium Uranium – Pressurized Heavy-Water is a registered trademark of Atomic Energy of Canada Limited.

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