INTRODUCTION

Everyone has temporarily lost their hold on a garden hose and observed the erratic motion occurring as long as water continues to flow through the hose. The motion of the unsupported garden hose results from flow-induced vibration. In addition to garden hoses, flow-induced vibration can occur in the long, heavy pipes hanging in underground storage caverns. The flow-induced vibration in storage cavern tubulars is a very complex issue and this paper only serves as an introduction to some of the complexities.

Nearly every solution-mined cavern has at least one long tubular hanging in the wellbore (and the cavern) from a support at the wellhead. The hanging tubular in liquid storage caverns is used to move product in and out of cavern storage with positive fluid displacement. Product is moved out of the cavern by injecting brine into the hanging tubulars in the well. When brine is flowing down the hanging tubular, product is moving out of the cavern through the annulus created by the hanging tubular and the wellbore cemented casing. Similarly, brine flows up the hanging tubular and out of the cavern when product is being injected into the cavern by way of the annulus.

The liquid storage industry is well aware that an upper limit exists for the fluid velocity in the injection tubulars in the storage caverns. If the injection velocity is gradually increased, eventually, the hanging tubular will experience unbounded flow-induced vibration, resulting in the potential for the hanging tubulars to bend and/or break off.

Many in the solution-mining and storage cavern business have adopted a “rule-of-thumb” maximum velocity limit in hanging tubulars of 15 feet per second (4.6 meters per second). This empirical limit, while clearly limiting the number of flow-induced, vibration-related tubing failures, has nonetheless not been rigorously justified from a theoretical basis.

The magnitude of the velocity limit for unbounded flow-induced vibration of liquid storage cavern hanging tubulars is not known. This creates a dilemma for the industry. While industry would most certainly like to maximize fluid velocities into and out of the caverns, industry clearly recognizes the enormous financial and business risk of haphazardly increasing the fluid velocities. In the absence of a clearly defined method for determining the maximum allowable fluid velocities in the liquid storage cavern tubulars, most operators have elected to adopt the maximum flow velocity based on “industry experience,” even though the “industry experience” database is unproven scientifically and sometimes consists primarily of tubulars far different in size from many being installed today.

It has long been recognized that fluid flow through a pipe at “high velocity” can produce vibration of the pipe. The vibration may dampen out with time, may continue at some “steady state” rate, or may sometimes increase without bound. The magnitude of the velocity that results in uncontrolled vibration depends on many factors, including the pipe support structure, the pipe and fluid properties, and the ambient temperature. Some of the important advancements in understanding this phenomenon have been generated by the engineering challenges of fluid flow in nuclear reactor components and oil flow in surface pipelines in the Middle East. The complexities of flow-induced vibration in tubulars have been addressed in the literature, and a brief bibliography is included with the references at the end of this paper. However, most of the literature addresses the problem from the standpoint of attempting to determine the “limiting velocity” that results in *unbounded* or *unstable* vibration.

In the storage cavern business, it is not enough to merely know the velocity at which uncontrolled vibration of the hanging string initiates. We are also concerned with the magnitude and duration of the *bounded* deformation and motion of the tubing resulting from fluid flow. This concern comes about because any deformation or motion in the injection string produces some level of bending stress in the hanging tubular. This bending stress can, in turn, result in tubing failure after many repeated cycles of flow into and out of the cavern.

In this paper, the theoretical basis for the governing equations for the transient flow-induced motion of hanging tubulars is introduced. This presentation of the governing equations is followed by a brief discussion of a successful solution strategy. Finally, several illustrative examples of static and transient deformation are presented. The paper concludes with a brief bibliography and cited references.